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IS 14869 (2000): Liquid Flow Measurement in Open Channels - Rectangular, Trapezoidal and U-Shaped Flumes [WRD 1: Hydrometry]



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अनावृत चैनल में द्रव प्रवाह मापन — आयताकार, समलंबी
और U-आकार लौ

Indian Standard

LIQUID FLOW MEASUREMENT IN OPEN
CHANNELS — RECTANGULAR, TRAPEZOIDAL
AND U-SHAPED FLUMES

ICS 17.120.20

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NEW DELHI 110002

NATIONAL FOREWORD

This Indian Standard which is identical with ISO 4359:1983 'Liquid flow measurement in open channels — Rectangular, trapezoidal and U-shaped flumes' issued by the International Organization for Standardization (ISO) was adopted by the Bureau of Indian Standards on the recommendations of the Fluid Flow Measurement Sectional Committee (WRD 01) and approval of the Water Resources Division Council. In the adopted standard, certain conventions are, however not identical to those used in Indian Standards. Attention is especially drawn to the following:

- a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.
- b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

Technical Corrigendum 1 to the above International Standard has been incorporated.

CROSS REFERENCES

In this adopted standard, the following International Standards have been referred to. Read in their respective places, the following Indian Standards:

<i>International Standard</i>	<i>Corresponding Indian Standard</i>	<i>Degree of Equivalence</i>
ISO 748 Liquid flow measurement in open channels — Velocity-area methods	IS 1192:1981 Velocity area methods for measurement of flow of water in open channels (first revision)	Identical with elucidation in Indian Standard (IS 1192:1981 is under revision based on ISO 748:1997 'Measurement of liquid flow in open channels — Velocity-area methods')
ISO 772 Liquid flow measurement in open channels — Vocabulary and symbols	IS 1191:1971 Glossary of terms and symbols used in connection with the measurement of liquid flow with a free surface (first revision)	Technically equivalent (IS 1191:1971 is under revision based on ISO 772:1996 'Hydrometric determinations — Vocabulary and symbols')
ISO 1438 Liquid flow measurement in open channels using thin-plate weirs and venturi flumes	IS 9108:1979 Liquid flow measurement in open channels using thin plate weirs	Technically equivalent to ISO 1438-1:1980 'Water flow measurement in open channels using weirs and venturi flumes: Part 1 Thin plate weirs

REFERENCES TO ERRORS AND CLARIFICATIONS IN TEXT

The Technical Committee while adopting the text of this International Standard identified certain textual errors to the following clauses and felt necessary to correct these in the Indian context:

<i>Clause Reference</i>	<i>Corrections</i>
9.4.1	Replace 'total head' by 'effective total head' in the first sentence.
10.1.5	Replace 'pont' by 'point' in the last line.
10.4.1	Line before equation (24) may be changed as 'Substitute (22) and (23) into (21)'.
10.6.1	Replace 'of ' by 'is' in the last sentence.
11.7.5(c)	Replace 'wherever the water surface lies' by 'at all water levels' in the last line.
D-4.8	Replace by 'Compute discharge for the given head from equation (44)'.
Fig. 2	Read the title as 'Geometry of Rectangular Throated Flume'.

Contents

	Page
1 Scope and field of application	1
2 References	1
3 Definitions and symbols	1
4 Units of measurement	1
5 Selection of the type of flume	1
6 Installation	2
6.1 Selection of site	2
6.2 Installation conditions	2
6.3 Flume structure	3
6.4 Downstream conditions	3
7 Maintenance — General requirements	3
8 Measurement of head	3
8.1 General requirements	3
8.2 Gauge well	4
8.3 Zero setting	4
9 Determination of discharge	4
9.1 General equations for discharge	4
9.2 Calculation of discharge from observed head	5
9.3 Calculation of stage-discharge relationships	5
9.4 Approach velocity	6
10 Rectangular throated flume	6
10.1 Description	6
10.2 Location of head measurement section	7
10.3 Provision for modular flow	7
10.4 Evaluation of discharge	7
10.5 Computation of stage-discharge relationship	8
10.6 Limits of application	8
10.7 Uncertainty of measurement	8

11	Trapezoidal throated flumes	8
11.1	Description	8
11.2	Location of head measurement section	9
11.3	Provision for modular flow	9
11.4	Evaluation of discharge	9
11.5	Computation of stage-discharge relationship	10
11.6	Graphical approach to design	11
11.7	Limits of application	11
11.8	Uncertainty of measurement	12
12	U-throated (round-bottomed) flumes	12
12.1	Description	12
12.2	Location of head measurement section	12
12.3	Provision for modular flow	12
12.4	Evaluation of discharge	13
12.5	Computation of stage-discharge relationship	14
12.6	Limits of application	15
12.7	Uncertainty of measurement	15
13	Errors in flow measurement	15
13.1	General	15
13.2	Sources of error	15
13.3	Kinds of error	16
13.4	Errors in coefficient values	16
13.5	Errors in measurement	16
13.6	Combination of uncertainties to give overall uncertainty on discharge	17

Annexes

A	Guide for the selection of weirs and flumes for the measurement of the discharge of water in open channels	18
B	Symbols and units	20
C	Velocity distribution	22
D	Computation of discharge using boundary layer theory	23
E	Examples illustrating methods for the computation of discharge	26
F	Example of the computation of the overall uncertainty of discharge measurement	30
G	Determination of height of hump — Rectangular throated flumes	31

Indian Standard

LIQUID FLOW MEASUREMENT IN OPEN CHANNELS — RECTANGULAR, TRAPEZOIDAL AND U-SHAPED FLUMES

1 Scope and field of application

This International Standard deals with the measurement of flow in rivers and artificial channels under steady or slowly varying flow conditions, using certain types of standing-wave (or critical depth) flumes. A wide variety of flumes has been designed but only those which have received general acceptance after adequate research and field testing, and which therefore do not require *in-situ* calibration are considered. Three types of flumes, covering a wide range of applications are recommended as follows :

- a) Rectangular-throated (see figure 1).
- b) Trapezoidal-throated (see figure 4).
- c) U-throated, i.e. round-bottomed (see figure 5).

The flow conditions considered are uniquely dependent on the upstream head, i.e. subcritical flow must exist upstream of the flume, after which the flow accelerates through the contraction and passes through its critical depth, and the water level beyond the structure is low enough to have no influence upon its performance.

Annex A gives the guidelines for the selection of weirs and flumes for the measurement of the discharge of water in open channels.

2 References

ISO 748, *Liquid flow measurement in open channels — Velocity-area methods.*

ISO 772, *Liquid flow measurement in open channels — Vocabulary and symbols.*

ISO 1438, *Liquid flow measurement in open channels using thin-plate weirs and venturi flumes.*

3 Definitions and symbols

For the purpose of this International Standard, the definitions given in ISO 772 apply. A full list of symbols with the corresponding units of measurement, is given in annex B.

4 Units of measurement

The units of measurement used in this International Standard are SI units.

5 Selection of the type of flume

5.1 The type of flume that should be used depends upon several factors, such as the range of discharge to be measured, the accuracy required, the head available and whether or not the flow carries sediment.

5.2 The rectangular-throated flume is simpler to construct. To achieve proportionality, i.e. to avoid either ponding or draw-down in the approach channel when the discharge is variable, provision of a hump in the bed becomes necessary with discharges bigger or smaller than the design discharge (see figure 2).

5.3 The trapezoidal-throated flume is more appropriate where a wide range of discharge is to be measured with consistent accuracy. This shape of throat is particularly suitable where it is necessary to work to a given stage-discharge relationship.

5.4 The U-throated flume is useful for installation in a U-shaped channel or where discharge is from a circular-section conduit. It has found particular application in sewers and at sewage works.

6 Installation

6.1 Selection of site

6.1.1 The flume shall be located in a straight section of channel, avoiding local obstructions, roughness or unevenness of the bed.

6.1.2 A preliminary study shall be made of the physical and hydraulic features of the proposed site, to check that it conforms (or can be constructed or modified so as to conform) to the requirements necessary for measurement of discharge by a flume. Particular attention should be paid to the following features in selecting the site :

- a) The adequacy of the length of channel of regular cross-section available.
- b) The uniformity of the existing velocity distribution (see annex C).
- c) The avoidance of a steep channel (but see 6.2.2).
- d) The effects of any increased upstream water levels due to the measuring structure.
- e) The conditions downstream (including such influences as tides, confluences with other streams, sluice gates, mill dams and other controlling features, including seasonal weed growth, which might cause drowning).
- f) The impermeability of the ground on which the structure is to be founded and the necessity for piling, grouting or other means of controlling seepage.
- g) The necessity for flood banks, to confine the maximum discharge to the channel.
- h) The stability of the banks, and the necessity for trimming and/or revetment.
- j) Uniformity of the section of the approach channel.
- k) Effect of wind, which can have a considerable effect on the flow over a river, weir or flume, especially when these are wide and the head is small and when the prevailing wind is in a transverse direction.
- m) Aquatic weed growth.
- n) Sediment transportation.

6.1.3 If the site does not possess the characteristics necessary for satisfactory measurements, or if an inspection of the stream shows that the velocity distribution in the approach channel deviates appreciably from the examples shown in annex C, the site should not be used unless suitable improvements are practicable. Alternatively, the performance of the installation should be checked by independent flow measurement.

6.2 Installation conditions

6.2.1 General requirements

6.2.1.1 The complete measuring installation shall consist of an approach channel, a flume structure and a downstream channel. The condition of each of these three components affects the overall accuracy of the measurements. Installation requirements include such features as the surface finish of the flume, the cross-sectional shape of the channel, channel roughness and the influence of control devices upstream or downstream of the gauging structure.

6.2.1.2 The distribution and direction of velocity may have an important influence on the performance of a flume (see 6.2.2 and annex C).

6.2.1.3 Once a flume has been installed, any changes in the system which affect the basis of the design will change the discharge characteristics.

6.2.2 Approach channel

6.2.2.1 If the flow in the approach channel is disturbed by irregularities in the boundary, for example large boulders or rock outcrops, or by a bend, sluice gate or other feature which causes asymmetry of discharge across the channel, the accuracy of gauging may be affected. The flow in the approach channel should have a symmetrical velocity distribution (see annex C) and this can most readily be achieved by providing a long straight approach channel of uniform cross-section.

6.2.2.2 A length of approach channel five times the water-surface width at maximum flow will usually suffice, provided flow does not enter the approach channel with high velocity via a sharp bend or angled sluice gate. However, a greater length of uniform approach channel is desirable if it can be readily provided.

6.2.2.3 The length of uniform approach channel suggested in 6.2.2.2 refers to the distance upstream of the head measuring position. However, in a natural channel it would be uneconomic to line the bed and banks with concrete for this distance, and it would be necessary to provide a contraction in plan if the width of the lined approach to the flume throat is less than the width of the natural channel. The unlined channel upstream of the contraction shall nevertheless comply with the requirements of 6.2.2.1 and 6.2.2.2.

6.2.2.4 Wing walls to effect a contraction in plan shall be symmetrically disposed with respect to the centre line of the channel and should preferably be curved with a radius not less than $2H_{\max}$. The downstream tangent point shall be at least $H_{\max}$ upstream of the head measurement section, and the lined section of approach channel from the end of the curved wing walls to the entrance transition of the flume shall be of prismatic section.

6.2.2.5 In a channel where the flow is free from floating and suspended debris, good approach conditions can also be provided by suitably placed baffles formed of vertical laths, but no baffle should be nearer to the point at which head is measured than $10H_{\max}$.

6.2.2.6 Under certain conditions a hydraulic jump may occur upstream of the measuring structure, for example if the approach channel is steep. Provided the hydraulic jump is at a distance upstream of not less than about $30H_{\max}$, flow measurement will be feasible, subject to confirmation that an even velocity distribution exists at the gauging section.

6.2.2.7 Conditions in the approach channel can be verified by inspection or measurement for which several methods are available such as floats, velocity rods, or concentrations of dye, the last being useful in checking conditions at the bottom of the channel. A complete and quantitative assessment of velocity distribution may be made by means of a current meter. The velocity distribution should then be assessed by reference to annex C.

6.3 Flume structure

6.3.1 The structure shall be rigid and watertight and capable of withstanding flood flow conditions without damage from outflanking or from downstream erosion. The axis shall be in line with the direction of flow of the upstream channel, and the geometry shall conform to the dimensions given in the relevant clauses.

6.3.2 The surfaces of the flume throat and the immediate approach channel shall be smooth : they can be constructed in concrete with a smooth cement finish or surfaced with a smooth non-corrodible material. In laboratory installations, the finish shall be equivalent to rolled sheet metal or planed, sanded and painted timber. The surface finish is of particular importance within the prismatic part of the throat but can be relaxed a distance along the profile $0,5H_{\max}$ upstream and downstream of the throat proper.

6.3.3 In order to minimise uncertainty in the discharge, the following tolerances are acceptable :

- a) On the bottom width of the throat, 0,2 % of this width with an absolute maximum of 0,01 m.
- b) On deviation from a plane of the plane surfaces in the throat, 0,1 % of L .
- c) On the width between vertical surfaces in the throat, 0,2 % of this width with a maximum of 0,01 m.
- d) On the average longitudinal and transverse slopes of the base of the throat 0,1 %.
- e) On a slope of inclined surfaces in the throat, 0,1 %.
- f) On a length of the throat, 1 % of L .
- g) On deviation from a cylindrical or a conical surface in the entrance transition to the throat, 0,1 % of L .

h) On deviation from a plane of the plane surfaces in the entrance transition to the throat, 0,1 % of L .

j) On deviation from a plane of the plane surfaces in the exit transition from the throat, 0,3 % of L .

k) On other vertical or inclined surfaces, deviation from a plane or curve, 1 %.

m) On deviation from a plane of the bed of the lined approach channel, 0,1 % of L .

The structure shall be measured on completion, and average values of relevant dimensions and their standard deviations at 95 % confidence limits computed. The former shall be used for computation of discharge and the latter shall be used to obtain the overall uncertainty in the determination of discharge (see 13.5).

6.4 Downstream conditions

The flow conditions downstream of the structure are important in that they control the tail water level which may influence the operation of the flume. The flume shall be so designed that it cannot become drowned under the operating conditions (see 10.3.1, 11.3.2 and 12.3.2). Construction of a flume in a river or stream may alter flow conditions and cause scouring downstream of the structure. This may result in accumulation of river bed material further downstream which, in time, may raise the normal water level sufficiently to drown the flume, particularly at low rates of flow. Any such accumulation of material shall be removed before it becomes excessive.

7 Maintenance — General requirements

Maintenance of the measuring structure and the approach channel is important to secure accurate continuous measurements.

It is essential that the approach channel to flumes shall be kept clean and free from silt and vegetation as far as practicable for at least the distance specified in 6.2.2.2. The float-well, and the entry from the approach channel shall also be kept clean and free from deposits.

The throat and the curved entry to a flume shall be kept clean and free from algal growths.

8 Measurement of head

8.1 General requirements

8.1.1 Where spot measurements are required, the head upstream of the flume throat can be measured by a vertical or inclined gauge, a hook, point, wire or tape gauge. Where a continuous record is required, a recording gauge shall be used. The location of the head measurement section is dealt with in 10.2, 11.2 and 12.2.

8.1.2 As the size of the flume and the head on it reduces, small errors in construction and in the zero setting and reading of the head measuring device become of greater relative importance.

8.2 Gauge well

8.2.1 It is usual to measure the head in a separate gauge well to reduce the effects of water surface irregularities. When this is done, it is also desirable to measure the head in the approach channel as a check.

8.2.2 The gauge well shall be vertical and of sufficient height and/or depth to cover the full range of water levels. In field installations it shall have a minimum margin of 0,3 m over the maximum water level estimated to be measured. At the recommended position for the measurement of head, the well shall be connected to the approach channel by means of a pipe or slot.

8.2.3 Both the well and the connecting pipe or slot shall be watertight, and where the well is designed for the accommodation of the float of a level recorder, it shall be of adequate size and depth to give clearance around the float at all stages. The float shall not be nearer than 0,075 m to the wall of the well.

8.2.4 The pipe or slot shall have its invert not less than 0,06 m below the lowest level to be gauged, and it shall terminate flush with the boundary of the approach channel and at right angles thereto. The approach channel boundary shall be plain and smooth (equivalent to carefully finished concrete) within a distance of ten times the diameter of the pipe or width of slot from the centre line of the connection. The pipe may be oblique to the wall only if it is fitted with a removable cap or plate, set flush with the wall, through which a number of holes are drilled. The edges of these holes shall not be rounded or burred.

8.2.5 Adequate additional depth shall be provided in the well to avoid the danger of the float grounding either on the bottom or on any accumulation of silt or debris. The gauge well arrangement may include an intermediate chamber of similar size and proportions between it and the approach channel, to enable silt and other debris to settle out where they may be readily seen and removed.

8.2.6 The diameter of the connecting pipe or width of slot shall be sufficient to permit the water level in the well to follow the rise and fall of head without appreciable delay, but on the other hand it shall be as small as possible consistent with ease of maintenance, to damp out oscillations due to short period waves.

8.2.7 No firm rule can be laid down for determining the size of the connecting pipe or slot, because this is dependent on the circumstances of the particular installation, for example whether the site is exposed and thus subject to waves, and whether a large diameter well is required to house the floats of recorders. It is preferable to make the connection too large rather than too small, because a restriction can easily be added later if short period waves are not adequately damped out. A

100 mm diameter pipe is usually suitable for a flow measurement in the field. A diameter of 3 mm may be appropriate in the laboratory.

8.3 Zero setting

8.3.1 Initial setting of the zero of the head-measuring device accurately with reference to the level of the invert of the throat, and regular checking of this setting thereafter, is essential if overall accuracy is to be attained.

8.3.2 An accurate means of checking the zero shall be provided. The instrument zero should be obtained by a direct reference to the throat invert, and a record of the setting made in the approach channel and in the gauge well. A zero check based on the water level (either when the flow ceases or just begins) is liable to serious errors due to surface tension effects and shall not be used.

9 Determination of discharge

9.1 General equations for discharge

9.1.1 Critical depth theory, augmented by experimental data, may be used to deduce the basic equations for free discharge through a streamlined contraction. The simple theory relates to the frictionless flow of an ideal fluid, and an additional coefficient has to be introduced in practice, either based on experiment or deduced by considering a modification to the simple theory, taking account of the boundary layer development with a real fluid such as water. This International Standard describes desk calculating methods for determining discharge but where many structures are being considered, computer analysis may be more appropriate.

9.1.2 The specific energy, E , of flow in an open channel is given by :

$$E = \beta d + \alpha \bar{v}^2 / 2g \quad \dots (1)$$

where

d is the depth of flow;

$\bar{v}$ is the average velocity through the section;

α is the coefficient taking into account non-uniformity in velocity distribution;

β is the coefficient dependent on the mean curvature of the streamlines.

The equation of continuity is :

$$Q = A\bar{v} \quad \dots (2)$$

where

Q is the total discharge;

A is the area of the flow cross-section.

Hence

$$E = \beta d + \alpha Q^2 / 2g A^2 \quad \dots (3)$$

Critical flow occurs when E has its minimum value for a given discharge Q , treating the depth d , and the area A which is related to it for any given cross-section geometry, as the variables. It can be shown that the specific energy is a minimum when

$$Q^2 = \frac{\beta g A^3}{\alpha w} \quad \dots (4)$$

where w is the water surface width.

9.1.3 Experimentally observed velocity profiles indicate that the velocity distribution is almost uniform in the throat of a flume, and it may be assumed therefore that $\alpha = 1$. If the streamlines are not significantly curved, a condition approached if the throat is in excess of a certain minimum length, then $\beta = 1$. Hence the basic equation defining critical flow through a streamlined contraction is

$$Q = (g A_c^3 / w_c)^{1/2} \quad \dots (5)$$

the subscript c indicating critical flow.

9.1.4 Equation (5) is not immediately applicable to the theoretical derivation of a stage-discharge relationship, because :

- it does not take account of the development of a boundary layer of slower moving fluid in the throat;
- it is based on the area and water surface width at the critical section, the location of which is ill-defined so that direct measurement of the water level at that section is impractical.

Thus the basic equation has to be transformed into a more practical form, and adjusted to take account of the boundary effects.

9.2 Calculation of discharge from observed head

9.2.1 For the flow of a real fluid through a streamlined rectangular contraction, equation (5) can be expressed in terms of the effective total head as follows :

$$Q = \left(\frac{2}{3} \right)^{3/2} b_e \sqrt{g} H_e^{3/2} \quad \dots (6)$$

where

b_e is the effective width of flume throat;

H_e is the effective total head.

9.2.2 Equation (6) can then be expressed in terms of h_e , the effective head gauged upstream of the structure, for flumes with rectangular throats as follows :

$$Q = \left(\frac{2}{3} \right)^{3/2} \sqrt{g} C_v b_e h_e^{3/2} \quad \dots (7)$$

where

$$C_v = (H_e / h_e)^{3/2} \quad \dots (8)$$

C_v is a dimensionless coefficient allowing for the effect of approach velocity on the measured water level upstream of the weir. Effective heads and widths can be determined from observed values

a) by a simple empirical correction (see 10.4.1, 11.4.1 and 12.4.1), or

b) by theoretical considerations of boundary layer development (see annex D).

9.2.3 Analogous relationships can be derived for flumes with trapezoidal throats :

$$Q = \left(\frac{2}{3} \right)^{3/2} \sqrt{g} C_v C_s b_e h_e^{3/2} \quad \dots (9)$$

where

C_s is a numerical coefficient which takes into account the non-rectangular flow section.

$$C_s = f(m H_{ce} / b_e) \quad \dots (10)$$

H_{ce} is the effective total head at critical section.

Although theoretical design and calibration procedures exist utilizing the above equations, they are cumbersome. This is largely because C_s is dependent on H_{ce} which differs significantly from the gauged head h . An alternative method of computing discharge from equation (5) is given in 11.5.

9.2.4 The corresponding relationship for U-throated flumes is :

$$Q = \left(\frac{2}{3} \right)^{3/2} \sqrt{g} C_v C_u D_e h_e^{3/2} \quad \dots (11)$$

where

C_u is a numerical constant which takes account of the non-rectangular flow section.

$$C_u = f(H_{ce} / D_e) \quad \dots (12)$$

D_e is the effective diameter of base of the U-shaped throat.

9.3 Calculation of stage-discharge relationships

9.3.1 In the case of a flume with a rectangular throat equation (7) has to be used to compute the stage-discharge relationship for the structure. However, equations (9) and (11) cannot conveniently be used to compute this relationship for trapezoidal and U-throated flumes. An alternative approach can be used.

9.3.2 A theoretical calibration for a gauging structure for the whole range of discharge can be derived by considering flow conditions in the throat of the flume and deducing corresponding heads and discharges. The principle of the method is to select a series of values of d_c the critical depth in the throat, and calculate corresponding values of Q and H_e using the expressions

$$Q = (g A_c^3 / w_c)^{1/2} \quad \dots (13)$$

and

$$H_e = d_c + \frac{A_c}{2w_c} \quad \dots (14)$$

The effective total head, H_e , can be converted to total head, H , as described in 11.5 and 12.5 and total head H , can be converted to measured gauged head, h , as outlined in 11.5 and 12.5.

9.4 Approach velocity

9.4.1 The total head is related to the gauged head by the equation :

$$H_e = h_e + \alpha \bar{v}_a^2 / 2g \quad \dots (15)$$

where

$\bar{v}_a$ is the mean velocity in the approach channel at the gauging section;

α is a coefficient (the kinetic energy or Coriolis coefficient) which takes account of the fact that the kinetic energy head exceeds $\bar{v}_a^2 / 2g$ if the velocity distribution across the section is not uniform.

In applying the equations in this International Standard, α may be taken as unity, with the tolerances given in 10.7.2, 11.8.2 and 12.7.2 and the provisions of 6.2.2 and bearing in mind annex C.

9.4.2 From equations (8) and (15), coupled with equations (7), (9) and (11), a general relationship for C_v may be defined by :

$$(C_v^{2/3} - 1)^{1/2} = \frac{2}{3\sqrt{3}} \times \frac{b_e h_e}{A} C_v C_{s \text{ or } u} \quad \dots (16)$$

where A is the cross-sectional area of the approach channel flow.

9.4.3 For a rectangular approach channel

$$A = B(h + p) \quad \dots (17)$$

where

B is the width of the approach channel;

p is the height of flume invert above the invert of the approach channel.

9.4.4 For a trapezoidal approach channel :

$$A = (h + p) [B + m_a(h + p)] \quad \dots (18)$$

where

B relates to the bed width of the approach channel;

m_a is the side slope of the approach channel walls.

9.4.5 For a U-shaped approach channel :

$$A = \frac{\pi}{4} D_a^2 f [(h + p)/D_a] \quad \dots (19)$$

where D_a is the diametrical width of the approach channel.

10 Rectangular throated flume

10.1 Description

10.1.1 The rectangular throated flume consists of a constriction of rectangular cross-section symmetrically disposed with respect to the approach channel.

This is the most common type of flume and the easiest to construct, but it cannot be adapted to suit non-rectangular channels when loss of head is important.

10.1.2 There are three types of rectangular throated flumes :

- with side contractions only;
- with bottom contraction or hump only;
- with both side and bottom contractions.

The type to be used depends on downstream conditions at various rates of flow, the maximum rate of flow, the permissible head loss and the limitations of the h/b ratio, and whether or not the stream carries sediment.

10.1.3 The invert of the throat shall be level throughout its width and length. The sides of the flume throat shall be vertical and parallel and square with the invert, so that the width of the throat is accurate from top to bottom and end to end. The surfaces of the throat and entrance transition shall be smooth; they may be constructed in concrete with a smooth finish, or lined with a smooth non-corrodible material. The centre line of the throat shall be in line with the centre line of the approach channel. In the case of flumes without a hump (bottom contraction), the floor of the approach channel shall be level, and at no point higher than the invert of the throat, for a distance of at least $2h_{\max}$ upstream of the head measurement section.

10.1.4 The flume geometry shall be as shown in figure 1. The radius of the curved transition to the bed and walls of the throat shall be at least $4p$ and $2(B - b)$ respectively. The 1 in 6 expansion beyond the throat may be truncated as shown in figure 1 when recovery of head is not important.

10.1.5 When the required recovery of head is more than 80 %, the alternative flume geometry with side and bottom contractions could be as shown in figure 2. The glacis slope downstream of the throat shall be 1 in 20 for a length of $2H$ (where H is the total head above the sill of the hump) beyond which it may be more. The length of the side walls downstream of throat shall be $4H$ and their divergence shall be 1 in 10. For greater recovery of heads, the side walls shall be parallel up to the toe of the glacis and then a hyperbolic expansion should be given up to the point where the downstream channel begins.

NOTE – When the ratio of the depth of water downstream above the sill of the throat to depth of water upstream over the sill of the throat is less than 0,5, a flumed standing wave fall (see figure 3) should be used with baffle platform, baffle wall, stilling basin and deflectors for efficient dissipation of energy.

10.2 Location of head measurement section

The head on the flume shall be measured at a point far enough upstream of the contraction to be clear of the effects of draw-down, but close enough to ensure that the energy loss between the section of measurement and the throat will be negligible. It is recommended that the head measurement section be located a distance of between 3 and 4 times $h_{\max}$ upstream of the leading edge of the entrance transition.

10.3 Provision for modular flow

10.3.1 Flow is modular when it is independent of variations in tail-water level, and for this to be so, the velocity has to be the critical velocity in the throat. The invert level shall therefore be at such an elevation as to produce modular flow for the full range of design discharges. The dimensions of the flume shall be such that the total head upstream (relative to throat invert) is at least 1,25 times that downstream (assuming subcritical flow exists downstream) at all rates of flow. Nevertheless, it may be possible to reduce this difference provided that the occurrence of free discharge is confirmed. On the other hand, if the expansion is truncated, the ratio shall be at least 1,33.

10.3.2 In artificial channels it is frequently possible to determine the depth downstream at various rates of flow with reasonable accuracy, for example by means of a friction formula if the channel is long enough and of constant slope or by reference to the characteristics of controlling features downstream.

If the flume is to be installed in an existing channel or stream the following information should then be obtained at the site :

- The maximum depth recorded with an estimate of the rate of flow at that depth.
- The approximate depths at two or more intermediate rates of flow.
- The dead water level in the stream, i.e. the level under zero flow conditions.

10.4 Evaluation of discharge

10.4.1 The basic discharge equation for rectangular throated flumes is given in 9.2.2 and this may be rewritten as :

$$Q = \left(\frac{2}{3}\right)^{3/2} \sqrt{g} C_v C_D b h^{3/2} \quad \dots (20)$$

where

$$C_D = \left(\frac{b_e}{b}\right) \left(\frac{h_e}{h}\right)^{3/2} \quad \dots (21)$$

but

$$b_e = b - 2\delta, \quad \dots (22)$$

$$h_e = h - \delta, \quad \dots (23)$$

where δ is the boundary layer displacement thickness.

Substituting from (22) to (23) into (21)

$$C_D = \left(1 - 2 \frac{\delta}{L} \times \frac{L}{b}\right) \left(1 - \frac{\delta}{L} \times \frac{L}{h}\right)^{3/2} \quad \dots (24)$$

where L is the length of prismatic section of the contraction at the flume.

For most installations with a good surface finish the value of δ/L will, in practice, lie in the range 0,002 to 0,004. Provided $10^5 > L/k_s > 4\,000$ and $Re > 2 \times 10^5$, δ/L may be assumed equal to 0,003.

Equation (24) then becomes :

$$C_D = \left(1 - \frac{0,006 L}{b}\right) \left(1 - \frac{0,003 L}{h}\right)^{3/2} \quad \dots (25)$$

Various values of C_D derived from this equation are given in table 1 and these are the values which apply to well-constructed installations as detailed above.

10.4.2 A more sophisticated approach is given in annex D which takes into account the development of the boundary layer in the throat of the flume. This enables the user to take into account the variability of δ/L and to use the more general expression for C_D given in equation (24).

10.4.3 The value of C_v can be computed from equations (16), (17), (22) and (23), or more conveniently, can be read from figure 6 or extracted from table 2 to a sufficiently close approximation. Figure 6 is expressed in terms of b_e , h_e and A , but in practice it will be found acceptable to use b and h in place of b_e and h_e in entering the diagram. Table 2 implicitly makes this assumption. In cases where the approach channel is not truly rectangular in section where h is measured, B can be determined from the expression :

$$B = \frac{\text{Cross-sectional area}}{h + p} \quad \dots (26)$$

10.4.4 The procedure indicated in 10.4.3 shall be adopted for calibration. For preliminary design purposes, however, in the case of the flume shown in figure 2, the discharge equation can be expressed as :

$$Q = \left(\frac{2}{3}\right)^{3/2} \sqrt{g} C b H^{3/2} \quad \dots (27)$$

where C is the overall coefficient and for design purposes may be assumed to have a value between 0,97 and 1,00.

When the structure is combined with a bridge having piers in the throat, the term b in equation (27) can be replaced by

$$(b - n_p b_p - 2C_c n_p H)$$

where

b_p is the width of pier;

n_p is the number of piers;

C_c is the coefficient of contraction
= 0,045 for piers with round nose
= 0,040 for piers with pointed nose.

10.5 Computation of stage-discharge relationship

10.5.1 The stage-discharge relationship for a rectangular throated flume is obtained by considering a series of values of gauged head, h , and repeating the method given in 10.4.1 to 10.4.3 for each. Corresponding gauged heads and discharges can then be plotted to provide the stage-discharge relationship for the flume.

10.6 Limits of application

10.6.1 The practical lower limit of h is related to the magnitude of the influence of fluid properties and boundary roughness. The recommended lower limit of 0,05 m or 0,05L, whichever is the greater.

10.6.2 There is also a limit on the ratio of the areas of the approach channel and the throat arising from difficulties experienced when the Froude number in the approach channel exceeds 0,5. The recommended upper limit of

$$\frac{bh}{B(h + p)}$$

is 0,7.

10.6.3 Other limitations arise from inadequate experimental confirmation for extreme sizes or geometries :

- b shall be not less than 0,10 m.
- h/b shall be not more than 3.
- h shall be not more than 2 m.

10.6.4 h/L should not exceed 0,50. This limitation on h/L arises from the necessity to ensure parallel flow conditions at the critical section in the throat. $h_{\max}/L$ may be allowed to rise to 0,67, with an additional uncertainty in coefficient of 2 %.

10.7 Uncertainty of measurement

10.7.1 The overall uncertainty of measurement will depend on :

- the standard of construction and finish of the flume;
- the uncertainty of the formula for the coefficient of discharge;
- the uncertainty of the velocity of approach coefficient;
- a correct application of the installation conditions;
- the uncertainty of the zero setting;
- the uncertainty of measurement of the geometry of the flume;
- the accuracy of the head gauge.

10.7.2 With reasonable skill and care in the construction of the flume, the coefficients are expected to have an uncertainty approaching 1 % in favourable circumstances, for example when C_D and C_v are not far from unity. An estimate of the combined percentage uncertainty (X_C) on the coefficients may be obtained from the equation :

$$X_C = \pm [1 + 20 (C_v - C_D)] \quad \dots (28)$$

10.7.3 The method by which the uncertainty of the coefficients is to be combined with the uncertainties due to other sources of error is explained in clause 13. [In applying equation (28), C_D is obtained from equation (25).]

11 Trapezoidal throated flumes

11.1 Description

11.1.1 Trapezoidal throated flumes can be designed to cope with many different flow conditions, and the optimum throat geometry (i.e. bed width and side slopes) will depend on the range of flow to be measured and on the characteristics of the stream or channel in which it is to be installed. Design methods by which the geometry might be selected to approximate to an existing or predetermined stage-discharge relation are outlined in 11.6.

11.1.2 Trapezoidal throated flumes should have a geometry generally as indicated in figure 4. In some circumstances, however, it will be appropriate to make the invert of the throat level with the invert of the approach channel, i.e. $p = 0$; this will be the case if sediment has to be conveyed through the flume. This International Standard covers only that class of trapezoidal throated flume in which the sloping walls of the throat extend above water level.

11.1.3 The flume shall be installed with the throat centre line in line with the centre of the approach channel. Subcritical flow shall exist in the flume approach, and the flume shall be

installed at such an elevation as to operate with free discharge throughout the range. The surfaces of the flume shall be of smooth concrete, galvanized steel or other smooth non-corrodible material. The throat section is of particular importance and shall have a level invert and be truly prismatic, the sloping walls being plane surfaces, symmetrically disposed and making a sharp intersection with the invert of the throat.

11.1.4 The entrance and exit transitions may be plane or curved surfaces to suit convenience of construction.

11.1.5 The convergence of the entrance transition on any plane section, if formed from plane surfaces, should not be more than 1 in 3 at each side. If curved surfaces are used, these shall be well-streamlined, for example by using the face of inclined cylinders, or a skew cylinder, or a vertical-axis cone. The surfaces shall lie entirely inside (i.e. on the channel centre-line side of) planes defining a 1 in 3 convergence on each side, and if curved shall terminate truly tangential to the planes forming the throat.

11.1.6 The surfaces forming the exit transition shall lie entirely inside planes defining a 1 in 3 expansion on each side. A 1 in 6 expansion gives very good recovery of head and a high modular limit.

11.2 Location of head measurement section

The head on the flume shall be measured at a point far enough upstream of the contraction to be clear of the effects of draw-down, but close enough to ensure that the energy loss between the section of measurement and the throat will be negligible. It is recommended that the head measurement section should be located a distance of between 3 and 4 times $h_{\max}$ upstream of the leading edge of the entrance transition.

11.3 Provision for modular flow

11.3.1 Flow is modular when it is independent of variations in tail-water level, and for this to be so, the velocity shall pass through the critical velocity in the throat. The invert level shall therefore be at such an elevation as to produce modular flow for the full range of design discharges. The dimensions of the flume shall be such that the total head upstream is well in excess of that downstream when related to the invert of the throat (assuming subcritical flow exists downstream).

11.3.2 As the modular limit is dependent on head recovery beyond the throat, the necessary ratio of upstream to downstream head is dependent on the angle of expansion, as follows :

1 in 20 each side $H/H_d > 1,10$

1 in 10 each side $H/H_d > 1,20$

1 in 6 each side $H/H_d > 1,25$

1 in 3 each side $H/H_d > 1,35$

where H_d is the total head just beyond the exit transition, related to the flume invert.

11.3.3 In artificial channels, it is frequently possible to determine the depth downstream at various rates of flow approximately, for example by means of a friction formula if the channel is long enough and of constant slope or by reference to the characteristics of controlling features downstream.

11.3.4 If the flume is to be installed in an existing channel or stream, the following information should then be obtained at the site :

a) The maximum depth recorded with an estimate of the rate of flow at that depth.

b) The approximate depths at two or more intermediate rates of flow.

c) The dead water level in the stream, i.e. the level under zero flow conditions.

11.4 Evaluation of discharge

11.4.1 The basic discharge equation for flumes with trapezoidal throated flumes is given in 9.2.3 and may be expressed as :

$$Q = \left(\frac{2}{3}\right)^{3/2} \sqrt{g} C_v C_s C_D b h^{3/2} \quad \dots (29)$$

The modular discharge coefficient, C_D , is given by an expression analogous to that for a rectangular flume as given in equation (24).

$$C_D = \left(1 - 2\eta \frac{\delta_s}{L} \times \frac{L}{b}\right) \left(1 - \frac{\delta_s}{L} \times \frac{L}{h}\right)^{3/2} \quad \dots (30)$$

where

η is a function of m ;

m is the slope of flume sides (m horizontal to 1 vertical).

For installations with a good surface finish δ_s/L can be taken as 0,003 and equation (30) reduces to

$$C_D = \left(1 - 0,006 \eta \frac{L}{b}\right) \left(1 - \frac{0,003 L}{h}\right)^{3/2} \quad \dots (31)$$

The value of η is obtained from figure 7 and the value of the modular discharge coefficient is then obtained by substituting known values of η , L , b and h in equation (31).

11.4.2 Annex D describes a method of determining C_D from equation (30) taking into account the variability of δ_s/L .

11.4.3 The value of C_v can be computed from equations (16) and (18) making the assumptions that $b_e = b$ and $h_e = h$. Alternatively, figure 6 may be used in association with the calculated value of A using equation (18).

11.4.4 The value of C_s to be inserted in equation (29) is a function of mH_{ce}/b_e and this is given in figure 8. If it were accurate to assume that $H_{ce} = h$, the gauged head, the use of the basic equation to evaluate discharge would be direct, though perhaps tedious. Initially it can be assumed that $H_{ce} = h$. However, to perform an accurate calibration, or accurately to deduce the discharge for a spot measurement of head, successive approximation is necessary, using the equation :

$$\frac{mH_{ce}}{b_e} = \frac{mh_e}{b_e} \times C_v^{2/3} \quad \dots (32)$$

For practical purposes it is sufficiently accurate to make the assumption that $h_e = h$ and $b_e = b$ giving a more readily usable expression :

$$\frac{mH_{ce}}{b_e} = \frac{mh}{b} \times C_v^{2/3} \quad \dots (33)$$

11.4.5 The computation of discharge to the first approximation for a given head acting on a trapezoidal flume of known geometry is thus made as follows :

- List the values of m , m_a , b , B , p , L and g .
- Compute the area of the approach channel cross-section using equation (17) or equation (18) or equation (19) depending on the shape of the approach channel.
- Calculate $\eta = \sqrt{(1 + m^2)} - m$, or obtain from figure 7.
- Calculate C_D from equation (31) using known values of η , L , b and h .
- As a first approximation, assume $mH_{ce}/b_e \approx mh/b$ and obtain C_s from figure 8 for the given value of h .
- Obtain the initial value of C_v from figure 6 assuming that $h_e \approx h$ and $b_e \approx b$ and entering the diagram at $C_s b h / A$.
- Calculate the first approximation value of Q using equation (29) with the above values of C_D , C_s and C_v .

11.4.6 Following the first approximation in 11.4.5 the values of C_s , C_v and Q need refining. C_D holds its final value. The next approximation proceeds as follows :

- mH_{ce}/b_e is obtained from equation (33).
- Figure 8 then provides the new value of C_s .
- $C_s b_e h_e / A$ can now be worked out (assuming $b_e \approx b$ and $h_e \approx h$), and a new value of C_v obtained from figure 6.
- The value of C_D , together with the revised values of C_v and C_s shall then be inserted in equation (29) to obtain a more accurate figure for Q .

11.4.7 The procedure carried out in 11.4.6 shall be repeated until sufficient precision has been obtained. An example of the method of computation of discharge is given in annex E.

11.5 Computation of stage-discharge relationship

11.5.1 Select a range of values of d_c the critical depth in the throat, (a roughly logarithmic series is more convenient than an arithmetic one) and for each value proceed as follows :

$$a) \quad w_c = b + 2md_c \quad \dots (34)$$

$$b) \quad A_c = (b + md_c) d_c \quad \dots (35)$$

c) Calculate Q using equation (13)

d) Calculate H_e using equation (14)

11.5.2 The next stage is to calculate the head correction, $H_* = H - H_e$. For installations with a good finish δ_*/L can be taken as 0.003 and H_* can be derived but substituting this value in the expression :

$$H_* = \frac{P_c}{w_c} \times \frac{\delta_*}{L} \times L \quad \dots (36)$$

where

$$P_c = b + 2d_c (1 + m^2)^{1/2} \quad \dots (37)$$

If the surface finish is not smooth the value of δ_*/L can be obtained as described in annex D. Substitution of the calculated value of δ_*/L in equation (36) gives the value of H_* taking into account the variability of δ_*/L .

11.5.3 For each value of d_c , calculate the total head, $H = H_e + H_*$. The values of Q and H derived in 11.5.1 and 11.5.2 provide the total head discharge relationship for the flume.

11.5.4 To convert from the total head, H , to gauged head, h , the expression

$$h = H - \frac{\bar{v}_a^2}{2g} \quad \dots (38)$$

shall be used, where $\bar{v}_a$ is the mean velocity in the approach channel at the gauging section. In applying equation (38), the geometry of the approach channel shall be used to compute its cross-sectional area A_a . Assuming this to be of trapezoidal section, the appropriate equation is

$$A_a = (h + p) [B + m_a (h + p)] \quad \dots (39)$$

where

p is the height of the hump at the throat;

B is the bed width of the approach channel;

m_a is its side slope (m_a horizontal to 1 vertical).

11.5.5 Because h occurs implicitly in the right hand side of equation (38), a method of successive approximation is needed to determine h .

First approximation :

Set $h = H$ and hence calculate A_{a1} from equation (39). Insert v_{a1} in equation (38), where $v_{a1} = Q/A_{a1}$, and thus obtain h_1 .

Second approximation :

Obtain A_{a2} from equation (39) inserting $h = h_1$. Hence $v_{a2} = Q/A_{a2}$ and $h_2 = H - v_{a2}^2/2g$.

Third approximation, etc.

Repeat procedure until $h_n - h_{n-1}$ is too small to have a significant effect on the accuracy.

11.5.6 Having thus worked out pairs of values of Q and h for a series of values of d_c , the calibration curve for the flume may be plotted to large logarithmic scales. Discharge values for intermediate values of h may be read off as necessary. Note that the calibration curve is not a straight line on a log-log plot.

11.5.7 An example of the calculation of the stage-discharge relationship for a trapezoidal flume (with and without boundary layer corrections) is given in annex E.

11.6 Graphical approach to design

11.6.1 There is considerable flexibility in the design of a trapezoidal throated flume, and this permits the designer to select values of m and b which will provide a close match to a predetermined relationship of head-to-discharge at two flows. For design purposes an approximate formula which effectively assumes $C_D = 1,0$ is adequate.

11.6.2 A convenient graphical method has been derived, using equation (29) in the form

$$\frac{Q}{\frac{2}{3} \sqrt{\left(\frac{2}{3}g\right) b H^{3/2}}} = f\left(\frac{mH}{b}\right) \quad \dots (40)$$

on the assumption that $H = H_c$ for design purposes.

11.6.3 Required values of Q and H are estimated from a knowledge or estimate of the existing stage-discharge relationship at the site, paying due regard to the head loss needed for free flow, practical limitations on the height of the throat above the stream bed (it shall not be below "no flow" level), and other limitations given. The two values of

$$\frac{Q}{\frac{2}{3} \sqrt{\left(\frac{2}{3}g\right) H^{3/2}}} \quad \dots (41)$$

corresponding to these boundary conditions are worked out and plotted on transparent material against H as abscissa on the same logarithmic scales as in figure 9.

11.6.4 Vertical and horizontal guidelines are added to the overlay and the $x = 1$ and $y = 1$ co-ordinates are marked. Move the overlay, keeping the axes parallel with figure 9, until the two plotted points lie on the curve. The intercept of $y = 1$ on the overlay with the y -axis of figure 9 gives $1/b$ and the intercept of $x = 1$ on the overlay with the x -axis of figure 9 gives m/b and hence m .

11.6.5 An example is shown by dotted lines for which $Q/\left[\frac{2}{3} \sqrt{\left(\frac{2}{3}g\right) H^{3/2}}\right]$ and H values are 3,07, 2,82m; 1,34, 0,21m; corresponding to discharges of 24,8 m³/s and 0,22 m³/s respectively. These requirements are met by a flume in which $b = 1,22m$ and $m = 0,90$.

11.7 Limits of application

11.7.1 The practical lower limit of h is related to the magnitude of the influence of fluid properties and boundary roughness. The recommended lower limit is 0,05 m or 0,05L, whichever is the greater.

11.7.2 h/L should not exceed 0,50. This limitation on h/L arises from the necessity to ensure parallel flow conditions at the critical section in the throat. $h_{\max}/L$ may be allowed to rise to 0,67 with an additional uncertainty in coefficient of 2 %.

11.7.3 The ratio of areas of the approach channel and the throat should preferably be such that the Froude number, Fr , in the approach channel does not exceed 0,5 at any discharge. This shall be checked at each end of the range, and at intermediate flows, using the equation

$$Fr_a = \bar{v}_a / \sqrt{(g A_a / w_a)} \quad \dots (42)$$

11.7.4 It may be necessary in some situations (for example where coarse sediment is being carried which would deposit in the approach channel) to allow Fr_a to rise to 0,6 but, because of surface irregularities at high Froude numbers, the measurement of head and performance of the flume are less certain, and an additional tolerance of 2 % should be allowed when $0,6 > Fr_a > 0,5$.

11.7.5 Other limitations arise from inadequate experimental confirmation for extreme sizes or geometries :

- b shall be not less than 0,1 m;
- h shall not be more than 2 m.
- At all elevations, the width between the throat walls shall be less than the width between the approach channel walls at the same elevation, i.e. there shall be a contraction wherever the water surface lies.
- The sloping walls of the throat shall continue upwards without change of slope far enough to contain the maximum discharge to be measured.

11.8 Uncertainty of measurement

11.8.1 The overall uncertainty of measurement will depend on :

- a) the standard of construction and finish of the flume;
- b) the uncertainty of the formula for the coefficient of discharge;
- c) the uncertainty of the velocity of approach coefficient;
- d) a correct application of the installation conditions;
- e) the uncertainty of the zero setting;
- f) the uncertainty of measurement of the geometry of the flume;
- g) the accuracy of the head gauge.

11.8.2 With reasonable skill and care in the construction of the flume the basic equation and coefficients are expected to have an uncertainty approaching 1 % in favourable circumstances, for example when C_D and C_v are not far from unity. An estimate of the combined percentage uncertainty X_C on the coefficients can be obtained from the equation :

$$X_C = \pm [1 + 20 (C_v - C_D)] \quad \dots (43)$$

11.8.3 The method by which the uncertainty in the coefficients is to be combined with uncertainties due to other sources of error is explained in clause 13. [In applying the above equation C_D is obtained from equation (31).]

12 U-throated (round-bottomed) flumes

12.1 Description

12.1.1 Flumes with their inverts in the form of a cylindrical surface with a horizontal axis cannot cope with such a wide variety of situations as the trapezoidal throated flume, but they have advantages over the rectangular throated flume in certain circumstances, for example in sewerage systems where the flow enters from a circular or U-shaped conduit. The sensitivity of a U-throated flume is greater than that of a rectangular throated flume, especially in the lower range of discharge lying within the lower semi-cylinder.

12.1.2 U-throated flumes shall have a geometry generally as indicated in figure 5. Two basic types are available when the approach channel is U-shaped also :

- a) A level invert arrangement in which no rise in invert level occurs at the throat.
- b) A raised invert level, in which the rise in invert level is half the difference in the diametrical widths of the approach channel and throat.

The former has advantages where heavy sediments are carried; the latter has the advantage of a simpler transition geometry.

12.1.3 The flume shall be installed with the throat centre line in line with the centre of the approach channel. Subcritical flow shall exist in the flume approach, and the flume shall be installed at such an elevation as to operate with free discharge throughout the range. The surfaces of the flume shall be of smooth concrete, galvanized steel or other smooth non-corrodible material. The throat section is of particular importance and shall have a level invert and be truly prismatic. The lower part shall accurately conform to the surface of a semi-cylinder, and the walls shall be plane vertical surfaces parallel to the axis of the semi-cylinder, the distance between them accurately matching the invert diameter.

12.1.4 The lower part of the entrance transition, if formed of a part-conical, or part of a skewed conical, surface shall generate a convergence in any plane radial to the flume axis of not more than 1 in 3. The upper part of the entrance transition, if formed of plane surfaces, shall converge at not more than 1 in 3 at each side. If curved surfaces are used, these shall be well-streamlined, for example generated by circular curves, and shall lie entirely inside the alternative part-conical part-plane entrance shown by the full lines in figure 5. They shall terminate truly tangential to the surfaces forming the throat.

12.1.5 The surfaces forming the exit transition shall lie within surfaces defining a 1 in 3 expansion. A 1 in 6 expansion gives very good recovery of head and a high modular limit.

12.2 Location of head measurement section

The head on the flume shall be measured at a point far enough upstream of the contraction to be clear of the effects of draw-down, but close enough to ensure that the energy loss between the section of measurement and the throat will be negligible. It is recommended that the head measurement section be located a distance of between 3 and 4 times $h_{\max}$ upstream of the leading edge of the entrance transition.

12.3 Provision for modular flow

12.3.1 Flow is modular when it is independent of variations in tail-water level, and for this to be so, the velocity must pass through the critical velocity in the throat. The invert level shall therefore be at such an elevation as to produce modular flow for the full range of design discharges. The dimensions of the flume shall be such that the total head upstream is well in excess of that downstream (related to the invert of the throat).

12.3.2 As the modular limit is dependent on head recovery beyond the throat, the necessary ratio of upstream to downstream head is dependent on the angle of expansion as follows :

$$\begin{aligned} 1 \text{ in } 6 \text{ each side } & H/H_d > 1.24 \\ 1 \text{ in } 3 \text{ each side } & H/H_d > 1.35 \end{aligned}$$

where H_d is the total head just beyond the exit transition, related to the flume invert.

12.3.3 In artificial channels it is frequently possible to determine the depth downstream at various rates of flow with

reasonable accuracy, for example by means of a friction formula if the channel is long enough and of constant slope or by reference to the characteristics of controlling features downstream.

12.3.4 If the flume is to be installed in an existing channel or stream, the following information shall then be obtained at the site :

- The maximum depth recorded with an estimate of the rate of flow at that depth.
- The approximate depths at two or more intermediate rates of flow.
- The dead water level in the stream, i.e. the level under zero flow conditions.

12.4 Evaluation of discharge

12.4.1 The basic discharge equation for U-throated flumes is given in 9.2.4 and this may be written as :

$$Q = \left(\frac{2}{3}\right)^{3/2} \sqrt{g} C_v C_u C_D D h^{3/2} \quad \dots (44)$$

where

$$C_D = \left(1 - 2\frac{\delta_*}{L} \times \frac{L}{D}\right) \left(1 - \frac{\delta_*}{L} \times \frac{L}{h}\right)^{3/2} \quad \dots (45)$$

For installations with a good surface finish δ_*/L can be taken as 0,003 and equation (45) reduces to the form

$$C_D = \left(1 - \frac{0,006L}{D}\right) \left(1 - \frac{0,003L}{h}\right)^{3/2} \quad \dots (46)$$

in order to compute Q for a given value of h , it is therefore necessary to evaluate the coefficients C_v , C_u and C_D .

12.4.2 The value of C_D is computed using equation (46) and known values of L , D and h . Annex D describes a method of determining C_D from equation (45) taking into account the variability of δ_*/L .

12.4.3 If it were correct to assume that $H_{ce} = h$, the gauged head (see figure 10) which expresses the shape coefficient C_u as a function of H_{ce}/D_e , would provide a value of C_u directly for a given head and throat diameter. Although the assumption $H_{ce} \approx h$ may be made for design purposes, or as a first approximation; to develop an accurate calibration, or to accurately deduce the discharge for a spot measurement of head, successive approximation is required, utilizing the equation :

$$\frac{H_{ce}}{h_e} = C_v^{2/3} \quad \dots (47)$$

For practical purposes it is sufficiently accurate to make the assumption that $h_e = h$. Hence :

$$\frac{H_{ce}}{h_e} \approx \frac{H_{ce}}{h} \approx C_v^{2/3} \quad \dots (48)$$

12.4.4 The value of C_v can be computed from equations (16) and (19) making the assumption that $h_e \approx h$ and $b_e \approx b$. Alternatively figure 6 gives a sufficiently close approximation. In entering figure 6, the value of C_u , as a first approximation, shall be read from figure 10 assuming $H_{ce}/D_e \approx h/D$.

12.4.5 The approach channel area required for the use in figure 6 is obtained from the geometry of the approach channel at the given water level. If the approach channel is U-shaped, and the water level lies within the semi-circular base portion :

$$\text{for } d_a < \frac{1}{2} D_a,$$

$$A_a = \frac{1}{4} D_a^2 (\theta - \sin \theta \cos \theta) \quad \dots (49)$$

where

$$\theta = \cos^{-1} \left(1 - \frac{2d_a}{D_a}\right) \quad \dots (50)$$

$$\text{for } d_a > \frac{1}{2} D_a,$$

$$A_a = \frac{\pi}{8} D_a^2 + \left(d_a - \frac{1}{2} D_a\right) D_a \quad \dots (51)$$

where $d_a = h + p$, i.e. the depth of water in the approach channel at the gauging section relative to the invert level at that point.

12.4.6 The computation of discharge for a given head acting on a U-shaped flume of known geometry thus proceeds as follows :

- List the values of D , L , D_a , p .
- Compute the area of the approach channel cross-section. If it is U-shaped, use equation (49) or (51).
- As a first approximation, assume $H_{ce}/D_e \approx h/D$ and obtain C_u from figure 10 for the given value of h .
- Calculate $C_u Dh/A$ and obtain a first approximation for C_v from figure 6.
- Compute C_D from equation (46).
- Calculate H_{ce} from equation (48) using the above value of C_v .

12.4.7 Following the first approximation in 12.4.6 the values of H_{ce} , C_v and C_u need refining. The next approximation proceeds as follows :

- Making the assumption that $D_e \approx D$, evaluate H_{ce}/D_e and obtain a new value of C_u from figure 10.
- Evaluate $C_u Dh/A$ and obtain a new value of C_v from figure 6.
- Calculate the new value of H_{ce} using equation (48).

12.4.8 Clause 12.4.7 shall be repeated until sufficient precision has been obtained.

12.4.9 Discharge is then computed from equation (44). (See example in annex E.)

12.5 Computation of stage-discharge relationship

12.5.1 For flow conditions for which $d_c \leq D/2$, select a series of values of θ , the semi-angle subtended at the centre of curvature of the invert by the water surface, between 0.5 and $\pi/2$ radians. For each angle, evaluate the depth, water surface width and cross-sectional area from :

$$a) \quad \frac{d_c}{D} = \frac{1}{2} (1 - \cos \theta) = f_1(\theta) \quad \dots (52)$$

$$b) \quad \frac{w_c}{D} = \sin \theta = f_2(\theta) \quad \dots (53)$$

$$c) \quad \frac{A_c}{D^2} = \frac{1}{4} (\theta - \sin \theta \cos \theta) = f_3(\theta) \quad \dots (54)$$

f_1, f_2, f_3 may be taken from table 3.

12.5.2 When $d_c > D/2$, water surface width and cross-sectional area are calculated for a range of values of d_c as follows :

$$a) \quad w_c = D \quad \dots (55)$$

$$b) \quad A_c = \frac{\pi}{8} D^2 + \left(d_c - \frac{1}{2} D \right) D \quad \dots (56)$$

12.5.3 The calculations described in 12.5.1 and 12.5.2 provide a series of corresponding values of d_c , w_c and A_c throughout the full range of a U-throated flume. The discharge, Q , and the effective upstream head, H_e , for each value of d_c can then be calculated using equations (13) and (14) respectively.

12.5.4 The next stage is to calculate the head correction, $H_s = H - H_e$. For installations with a good surface finish, δ_s/L can be taken as 0.003 and H_s can be derived by substituting this value in the expression :

$$H_s = \frac{P_c}{w_c} \times \frac{\delta_s}{L} \times L \quad \dots (57)$$

where

$$P_c = D\theta \quad \dots (58)$$

or

$$P_c = \frac{\pi D}{2} + 2 \left(d_c - \frac{1}{2} D \right) \quad \dots (59)$$

Equation (58) applies when $d_c \leq D/2$ ($\theta \leq \pi/2$) and equation (59) applies when $d_c > D/2$. If the surface finish is not

smooth, the value of δ_s/L can be obtained as described in annex D. Substitution of the calculated value of δ_s/L in equation (57) gives the value of H_s taking into account the variability of δ_s/L .

12.5.5 For each value of d_c , calculate the total head, $H = H_e + H_s$. The values of Q and H derived in 12.5.3 and 12.5.5 provide the total head/discharge relationship for the flume.

12.5.6 To convert from total head, H , to gauged head, h , the expression

$$h = H - \frac{\bar{v}_a^2}{2g} \quad \dots (60)$$

shall be used, where $\bar{v}_a$ is the mean velocity in the approach channel at the gauging section. For applying equation (60), the geometry of the approach channel shall be used to compute its cross-sectional area A_a . Assuming this to be of U-shape, the appropriate equations are :

$$\frac{A_a}{D_a^2} = \frac{1}{4} (\theta_a - \sin \theta_a \cos \theta_a) = f_3(\theta_a) \quad \dots (61)$$

$$\text{with } \theta_a = \arccos \left(\frac{\frac{1}{2} D_a - h - p}{\frac{1}{2} D_a} \right)$$

when $(h + p) \leq D_a/2$

and

$$A_a = \frac{\pi}{8} D_a^2 + (h - \frac{1}{2} D_a) D_a \quad \dots (62)$$

when $(h + p) > D_a/2$

where θ_a is the semi-angle subtended at the centre of curvature of the invert of the approach channel by the water surface, D_a is the width of the approach channel and p is the height of the hump at the throat.

12.5.7 Because h occurs implicitly in the right hand side of equation (60), a method of successive approximation is needed to work out h .

First approximation :

Set $h = H$ and hence calculate A_{a1} from either equation (61) or equation (62). Insert $\bar{v}_{a1}$ in equation (60), where $\bar{v}_{a1} = Q/A_{a1}$, and thus obtain h_1 .

Second approximation :

Obtain A_{a2} from equation (61) or (62) inserting $h = h_1$. Hence $\bar{v}_{a2} = Q/A_{a2}$ and $h_2 = H - \bar{v}_{a2}^2/2g$.

Third approximation, etc. :

Repeat procedure until $h_n - h_{n-1}$ is too small to have a significant effect on the accuracy.

12.5.8 Having thus worked out pairs of values of Q and h for a series of values of d_c , the calibration curve for the flume may be plotted to large logarithmic scales. Discharge values for intermediate values of h may be read off as necessary. Note that the calibration curve is not a straight line on a log-log plot.

12.5.9 An example of the calculation of the stage-discharge relationship for a U-throated flume (with and without boundary layer corrections) is given in annex E.

12.6 Limits of application

12.6.1 The practical lower limit of h is related to the magnitude of the influence of fluid properties and boundary roughness. The recommended lower limit is 0,05 m or 0,05 L whichever is the greater.

12.6.2 h/L should not exceed 0,50. This limitation on h/L arises from the necessity to ensure parallel flow conditions at the critical section in the throat. $h_{\max}/L$ may be allowed to rise to 0,67, with an additional uncertainty in coefficient of 2 %.

12.6.3 The ratio of areas of the approach channel and the throat should preferably be such that the Froude number, Fr , in the approach channel does not exceed 0,5 at any discharge. This shall be checked at each end of the range, and at intermediate flows, using the equation :

$$Fr_a = \bar{v}_a / \sqrt{(g A_a / w_a)} \quad \dots (63)$$

12.6.4 It may be necessary in some situations (for example where coarse sediment is being carried which would deposit in the approach channel) to allow Fr_a to rise to 0,6 but, because of surface irregularities at high Froude numbers, the measurement of head and performance of the flume are less certain, and an additional tolerance of 2 % should be allowed when $0,6 > Fr_a > 0,5$.

12.6.5 Other limitations arise from inadequate experimental confirmation for extreme sizes or geometries :

- a) D shall be at least 0,1 m.
- b) h shall be not more than 2 m.
- c) At all elevations, the width between the throat walls shall be less than the width between the approach channel walls at the same elevation, i.e. there shall be a contraction wherever the water surface lies.

12.7 Uncertainty of measurement

12.7.1 The overall uncertainty of measurement will depend on :

- a) the standard of construction and finish of the flume;
- b) the uncertainty of the formula for the coefficient of discharge;

- c) the uncertainty of the velocity of approach coefficient;
- d) a correct application of the installation conditions;
- e) the uncertainty of the zero setting;
- f) the uncertainty of measurement of the geometry of the flume;
- g) the accuracy of the head gauge.

12.7.2 With reasonable skill and care in the construction of the flume, the basic equation and coefficients are expected to have an uncertainty approaching 1 % in favourable circumstances, for example when C_D and C_V are not far from unity. An estimate of the combined percentage uncertainty (X_C) on the coefficients may be obtained from the equation :

$$X_C = \pm [1 + 20 (C_V - C_D)] \% \quad \dots (64)$$

12.7.3 The method by which the uncertainty of the coefficients is to be combined with the uncertainties due to other sources of uncertainty is explained in clause 13.

13 Errors in flow measurement

13.1 General

13.1.1 The total uncertainty of any flow measurement can be estimated if the uncertainties from various sources are combined. The assessment of these contributions to the total uncertainty will indicate whether the rate of flow can be measured with sufficient accuracy for the purpose in hand. This clause is intended to provide sufficient information for the user of this International Standard to estimate the uncertainty in a measurement of discharge (see ISO 5168).

13.1.2 The error may be defined as the difference between the true rate of flow and that calculated in accordance with the equations used for calibrating the flume, which is assumed to be constructed and installed in accordance with this International Standard. The term uncertainty is here used to denote the deviation from the true rate of flow within which the measured flow is expected to lie some nineteen times out of twenty (with 95 % confidence limits).

13.2 Sources of error

13.2.1 The sources of error in the discharge measurement may be identified by considering a generalized form of discharge equation for flumes

$$Q = \left(\frac{2}{3} \right)^{3/2} C_D C_V C_S b \sqrt{g} h^{3/2} \quad \dots (65)$$

NOTE — For U-throated flumes C_S is replaced by C_U , and $b = D$. $(2/3)^{3/2}$ is a numerical constant not subject to error; g , the acceleration due to gravity, varies from place to place, but the variation may be neglected in flow measurement.

13.2.2 The only sources of error which need to be considered further are :

- a) The discharge coefficient C_D and the velocity of approach coefficient C_v . Numerical estimates and uncertainties in the combined coefficient $C_v C_D$ are given in 10.7, 11.8 and 12.7.
- b) The shape coefficient, C_s , for a trapezoidal throated flume or C_u , for a U-throated flume, is assumed to be accurately computed. The combined percentage uncertainty X_C is assumed to be covered by the uncertainties in the coefficients $C_D C_v$. However, C_s is dependent on a knowledge of the side slope, m , and allowance shall be made for inaccuracy in estimating m .
- c) The dimensional measurement of the structure, for example the bed width of the flume, b , or the diameter of the U-throated flume, D .
- d) The measured head, h .

13.2.3 The uncertainties in b (or D) and h have to be estimated by the user. The uncertainty in dimension will depend upon the accuracy to which the device as constructed can be measured; in practice this uncertainty may prove to be insignificant in comparison with other uncertainties. The uncertainty in the head will depend upon the accuracy of the head-measuring device, the determination of the gauge zero, and upon the technique used. This may be small if a vernier or micrometer instrument is used, with a zero determination of comparable precision.

13.3 Kinds of error

13.3.1 Errors can be classified as random or systematic, the former affecting the reproducibility (precision) of measurement and the latter affecting its true accuracy.

13.3.2 The standard deviation of a set of n measurements of a quantity Y under steady conditions may be estimated from the equation

$$s_Y = \left[\frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n - 1} \right]^{1/2}, \quad \dots (66)$$

where $\bar{y}$ is the arithmetic mean of the n measurements.

The standard deviation of the mean is then given by :

$$s_{\bar{Y}} = \frac{s_Y}{\sqrt{n}} \quad \dots (67)$$

and the uncertainty of the mean is twice $s_{\bar{Y}}$ (to 95 % probability)¹⁾. This uncertainty is the contribution of the observations of Y to the total uncertainty.

13.3.3 A measurement may also be subject to systematic error; the mean of very many measured values would thus still differ from the true value of the quantity being measured. An error in setting the zero of a water level gauge to invert level, for example, produces a systematic difference between the true mean measured head and the actual value. As repetition of the measurement does not eliminate systematic errors, the actual value can only be determined by an independent measurement known to be more accurate.

13.4 Errors in coefficient values

13.4.1 All errors in this category are systematic.

13.4.2 The values of the various coefficients quoted in this International Standard are derived from theoretical considerations. The limitations quoted are those necessary to restrict application to those conditions where experiment has shown that the theory of critical flow and the assessment of boundary layer displacement thickness are applicable.

13.4.3 The uncertainties in the coefficients quoted in the preceding sections of this International Standard are based on an assessment of the uncertainties in the estimate of boundary layer displacement thickness, in the allowance for approach velocity and in the use of graphs for C_u , C_s , etc. The deviation of experimental data from various sources from theoretical prediction is consistent with these suggested values of uncertainty.

13.5 Errors in measurement

13.5.1 Both random and systematic errors will occur in measurements made by the user.

13.5.2 Since neither the methods of measurement nor the way in which they are to be made are specified, no numerical values for uncertainties in this category can be given; they have to be estimated by the user. For example, consideration of the method of measuring the flume should permit the user to determine the uncertainties in the bed width, b , the side-slope m in the case of trapezoidal throated flumes, and the diameter D of a U-throated flume.

13.5.3 The discharges given by the equations are volumetric figures, and the fluid density does not affect the volumetric discharge for a given head provided the operative head is gauged in fluid of identical density. If the gauging is carried out in a separate well, a correction for the difference in density may be necessary if the temperature in the well is significantly different from that of the flowing fluid. However, it is assumed herein that the densities are equal.

13.5.4 The uncertainty of the gauged head should be determined from an assessment of the separate sources of uncertainty, for example the zero uncertainty, the gauge sensitivity,

1) This factor of two assumes that n is large. For $n = 6$ the factor should be 2.6; $n = 8$ requires 2.4; $n = 10$ requires 2.3; $n = 15$ requires 2.1.

backlash in the indication mechanism, the residual random uncertainty in the mean of a series of measurements, etc. The uncertainty of the gauged head is the square root of the sum of the squares of the separate uncertainties.

13.5.5 The above component uncertainties should be calculated at the 95 % confidence limits but when the value of a component uncertainty is determined from only a single measurement, it is said to be rectangularly distributed and the uncertainty may be taken, for the purpose of this International Standard, to be the (plus or minus) limits within which the true value is known to lie (i.e. half the estimated maximum deviation).

13.6 Combination of uncertainties to give overall uncertainty on discharge

13.6.1 The total uncertainty is the resultant of several contributory uncertainties, which may themselves be composite uncertainties (see 13.5.4).

13.6.2 The uncertainty of the rate of flow shall be calculated from the following equation :

$$X = \pm \sqrt{(X_C^2 + \gamma^2 X_b^2 + \phi^2 X_h^2 + \psi^2 X_m^2)} \quad \dots (68)$$

where

X_C is the percentage uncertainty in $C_v C_D$;

X_b is the percentage uncertainty in b (or D);

X_h is the percentage uncertainty in h ;

X_m is the percentage uncertainty in m .

γ , ϕ and ψ are numerical coefficients depending on the flume geometry. In the simple case of a rectangular flume, $\gamma = 1$, $\phi = 1.5$, and $\psi = 0$ (assuming the walls are truly vertical). For a trapezoidal throated flume, γ and ψ depend on mH_c/b , and are shown in figure 11. For a U-throated flume, $\psi = 0$ (assuming the walls are truly vertical); γ and ϕ depend on H_c/D and are shown in figure 11. (In using these curves, the approximation $H_c \approx h$ may be used.)

In the above

$$X_b = \pm 100 \times \frac{\varepsilon_b}{b} \quad \dots (69)$$

$$X_h = \pm \frac{100 [\varepsilon_h^2 + 2\varepsilon_h'^2 + \dots (2S_{\bar{h}})^2]^{1/2}}{h} \quad \dots (70)$$

where

ε_b is the uncertainty in width measurement;

ε_h , ε_h' , etc., are uncertainties in head measurement (see 13.5.4);

$2S_{\bar{h}}$ is the uncertainty of the mean if a series of readings of the head measurement are taken (see 13.3.2 including footnote).

13.6.3 It should be realized that the uncertainty X is not a single value for a given device, but will vary with discharge. It may therefore be necessary to consider the uncertainty at several discharges covering the required range of measurement.

13.6.4 An example of the calculation of the combined uncertainties is given in annex F.

Annex A

Guide for the selection of weirs and flumes for the measurement of the discharge of water in open channels

A.1 Scope and field of application

This annex lays down guidelines for the selection of weirs and flumes for the measurement of discharge in open channels. Consideration is limited to the steady, uniform flow of water at ordinary temperatures (approximately 5 to 30 °C).

Despite the great number of types of weirs and flumes available, some of which may offer advantages for specific purposes, only the following types are presently standardized. Criteria for selection from among the standard types are given in clause A.3.

A.2 Types of standard weirs and flumes

A.2.1 Thin-plate weir

A weir constructed with a crest of vertical thin plate, shaped in such a manner that the nappe springs clear of the crest, the discharge being determined by the head on the weir and the width of the crest (or the angle of the notch).

The following types are included :

- rectangular full-width weir;
- rectangular-notch weir;
- triangular-notch (V-notch) weir.

A.2.2 Broad-crested weir

A weir with substantial crest dimension in the direction of flow formed in such a manner that critical flow occurs on the crest of the weir within the breadth, the discharge being determined by the head on the weir and the width of the crest.

The following types are included :

- rectangular-profile weir with sharp upstream edge;
- rectangular-profile weir with rounded upstream edge.

A.2.3 Triangular-profile weir

A weir having a triangular profile in the direction of flow, the discharge being determined by the head over the weir and the width of the crest.

The following type is included :

- triangular-profile weir having 1:2 slope upstream and 1:5 slope downstream.

A.2.4 Standing-wave flume (free flow)

A flume with side contractions with or without bottom contractions, within which the flow changes from sub-critical to super-critical, the discharge being determined by the cross-sectional area and velocity of flow at critical depth within the throat of the flume.

The following types are included :

- with rectangular throat;
- with trapezoidal throat;
- with U-throat.

A.2.5 Free overfall

An abrupt drop in the floor of a rectangular channel, the discharge being determined by the depth at the brink of the drop and the width of the channel at the brink section.

A.3 Criteria for selection of standard weirs or flumes

The essential criteria for selection from among the standard weirs and flumes are given below.

A.3.1 Available difference in water levels

Thin-plate weirs and free overfalls require a sufficient difference between upstream and downstream water levels which ensure free, fully ventilated flow under conditions of maximum discharge.

Broad-crested weirs may be used with relatively smaller differences in water level; triangular-profile weirs and standing-wave flumes may be used with even smaller differences in water level.

For all types of weirs and flumes included in this International Standard, the discharge should be free or independent of the downstream water level.

A.3.2 Accuracy of measurement

The accuracy in a single determination of discharge depends upon the estimation of the component uncertainties involved but approximate ranges of uncertainties for the weirs and flumes (at 95 % confidence levels) are as follows :

- rectangular thin-plate weirs (full-width and notch) 1 to 4 %;

- triangular-notch weirs (notch angles between 20° and 100°) 1 to 2 %;
- broad-crested weirs 3 to 5 %;
- triangular-profile weirs 2 to 5 %;
- standing-wave flumes 2 to 5 %;
- free overfall 5 to 10 %.

Deviations from standard construction, installation or use may result in larger measurement errors. The larger figures given above are recommended conservative values for use under conditions of strict conformance with standard specifications. The smallest values can only be obtained for weirs under rigorous control, such as may be built and installed in well-equipped laboratories. Under field conditions, thin-plate weirs are specially subject to errors caused by natural hazards.

A.3.3 Dimensions and shape of open channel

Rectangular full-width weirs and notch weirs (both rectangular and triangular) of large size relative to the size of the approach channel, should be located in vertical-walled, level-floored rectangular channels, or in weir boxes of rectangular cross-section for a distance extending upstream not less than ten times the width of the nappe at maximum head. For thin-plate weirs of small size relative to the size of the approach channel, especially if the velocity of approach is negligible, the size and shape of the channel is of no importance.

Broad-crested weirs are best used in rectangular channels, but they can be used with good accuracy in non-rectangular channels if a smooth, rectangular approach channel extends upstream from the weir by a distance not less than twice the maximum head.

Flumes can be used in channels of any shape if flow conditions in the approach channel are reasonably uniform and steady.

For weirs and flumes of all types, the size and shape of the downstream channel are of no significance except that they must permit free, fully ventilated flow under all conditions of use.

A.3.4 Flow conditions in the approach channel

For weirs of all types, flow in the approach channel shall be sub-critical, uniform and steady. Ideally, especially for relatively high velocities of approach, the velocity distribution should approximate that in a channel of sufficient length to develop normal (resistance-controlled) flow in straight, smooth channels. For relatively low velocities of approach and for flumes, flow conditions in the channel are of less importance. In short channels and weir boxes, baffles and flow-straighteners may be used to establish a normal velocity distribution. Care should be taken to ensure that erosion and/or deposition upstream of the weir or flume do not significantly alter the velocity of approach or velocity distribution to the measurement structure.

Sub-critical flow is ensured when

$$\bar{v} < \sqrt{\frac{gA}{B_s}}$$

where

$\bar{v}$ is the average velocity, in metres per second, in the approach channel;

g is the acceleration due to gravity, in metres per second squared;

A is the cross-sectional area, in square metres, of the channel;

B_s is the width of the channel, in metres, at the water surface.

A.3.5 Flow with sediment load

For flows with suspended load, the use of thin-plate weirs should be avoided because the crest edge may be damaged or worn by the suspended materials.

On streams with bed load, the use of measurement structures which significantly reduce the stream velocity is not recommended as it may result in changing deposition scour dependent on flow regime. Flumes will generally perform better than weirs on streams with sediment load.

A.3.6 Flow with floating debris

Broad crested weirs, triangular profile weirs, standing wave flumes and free overfall structures will normally pass floating debris more effectively than thin-plate weirs. The use of the triangular-notch (V-notch) weir in particular should be avoided unless a debris trap is installed upstream.

A.3.7 Magnitude of discharge to be measured

For reasons related to accuracy and construction, thin-plate weirs are best used for the measurement of relatively small discharges. Broad-crested weirs, triangular-profile weirs and flumes are best used for large discharges.

A.3.8 Range of discharge to be measured

For best overall accuracy over a wide range of small discharges, a triangular-notch (V-notch) weir should be used in preference to a rectangular-notch or rectangular full-width weir. For a wide range of larger discharge, a trapezoidal-throat or U-throat flumes should be used in preference to a broad-crested weir, free overfall, rectangular-throated flume or a triangular-profile weir.

A.3.9 Construction

Thin-plate weirs should be constructed with precision tools under machine-shop conditions. Flumes, broad-crested weirs, triangular-profile weirs and free overfalls can be constructed satisfactorily in the field. In all cases, great care must be exercised in making the structures conform with standard specifications.

Broad-crested weirs, triangular-profile weirs, free overfalls and flumes are inherently stronger and more easily maintained under conditions of high heads in large channels.

Annex B

Symbols and units

Units of measurement are metres (m) and seconds (s) or derivatives of these.

Symbol	Quantity	Unit of measurement
A	area of cross-section of flow	m ²
B	width of approach channel (width at bed if trapezoidal)	m
b	width of flume throat (width at bed if trapezoidal)	m
b_p	width of piers	m
C	overall coefficient of discharge (rectangular flumes)	non-dimensional
C_c	coefficient of contraction	non-dimensional
C_D	coefficient of discharge	non-dimensional
C_s	shape coefficient for trapezoidal throated flumes	non-dimensional
C_u	shape coefficient for U-shaped throated flumes	non-dimensional
C_v	coefficient allowing for the effect of approach velocity	non-dimensional
C_1	coefficient of discharge for channels	non-dimensional
D	diameter of base of U-shaped throated flumes	m
d	depth of flow	m
E	specific energy	m
e	a measure of the excess of the maximum velocity in a section over the mean	non-dimensional
Fr	Froude number = $\frac{\bar{v}}{\sqrt{gd}}$	non-dimensional
f_1, f_2, f_3 , etc.	geometric functions depending on θ	non-dimensional
g	gravitational acceleration	m/s ²
H	total head	m
H_s	correction to the total head	m
h	gauged head	m
J	fraction of discharge	non-dimensional
k_s	equivalent sand-roughness of surface, after Nikuradse	m
L	length of prismatic section of the contraction at a flume	m
L_b	length of baffle platform	m
L_1	length of bellmouth entrance	m
L_2	length of glacis	m
L_3	length of stilling basin	m
m	side-slope (m horizontal to 1 vertical)	non-dimensional

Symbol	Quantity	Unit of measurement
n	number of measurements in series	non-dimensional
n_p	number of piers	
P	wetted perimeter of flow cross-section	m
p	height of flume invert above the invert of the approach channel	m
Q	discharge	m ³ /s
R	radius	m
Re	Reynolds number	non-dimensional
r_p	radius of hump	m
R_1	radius of bellmouth entrance	m
$\bar{v}$	average velocity through a cross-section, defined by Q/A	m/s
w	water surface width	m
X	overall uncertainty in the determination of discharge expressed as a percentage standard deviation at 95 % confidence limits	non-dimensional
X_b	uncertainty in b (or D)	non-dimensional
X_C	uncertainty in the combined coefficient value	non-dimensional
X_h	uncertainty in h	non-dimensional
X_m	uncertainty in m	non-dimensional
z	index of d in formula for canal discharge	non-dimensional
α	coefficient taking into account non-uniformity of velocity distribution	non-dimensional
β	coefficient dependent on mean curvature of stream lines	non-dimensional
γ, ϕ, ψ	coefficients in the error equation	
δ_s	boundary layer displacement thickness	m
η	a numerical coefficient	non-dimensional
ν	kinematic viscosity of the fluid	m ² /s
S	standard deviation	—
$\bar{S}$	standard error of the mean	—
θ	semi-angle subtended at the centre of curvature of the invert of a U-shaped flume by the water surface	non-dimensional
ε_b	uncertainty in width measurement	m
ε_h	uncertainty in head measurement	m
Subscripts		
a	values in approach channel	
c	values at critical flow	
d	values downstream of the flume	
e	effective values after making allowance for boundary layer effects	
1	values assuming an ideal frictionless fluid	
max.	the maximum value	

Annex C

Velocity distribution

C.1 An even distribution of velocity over the cross-section of the approach channel in the region of the gauging station is necessary for high accuracy of measurement of discharge by means of weirs, notches and flumes. This is because the recommended coefficients are empirical values obtained by various investigators and were usually obtained under ideal laboratory conditions. These involved either the use of screens to ensure an approximately uniform velocity over the cross-section, or a long straight approach channel conducive to the establishment of a normal distribution of velocities.

C.2 Normal velocity distribution is defined as the distribution of velocities attained in a channel over a long uniform straight reach. A characteristic feature of flow in such a channel is that the velocity is a maximum at about 0,6 depth above invert, with the average velocity occurring at about 0,4 depth above invert.

C.3 Any deviation from the ideal conditions of either very uniform velocity or a normal velocity distribution may lead to errors in flow measurement, but quantitative information on the influence of velocity distribution is inadequate to define the acceptable limits of departure from the ideal distribution. With the uncertainties on discharge coefficients quoted in 10.7, 11.8

and 12.7 in mind, figure 12 provides some guidance to the type of velocity distribution and evenness thereof that are acceptable in practice.

C.4 In figure 12 different patterns of isovels are shown. These isovels are contours of equal velocity in the direction of flow.

C.5 The isovels plotted in figures 12d), e) and f) provide examples of observed normal velocity distributions, which are clearly acceptable. Figure 12a) shows some skewness, but nevertheless approximates to a normal distribution. Figures 12b) and 12c) show appreciable departure from uniformity, and are considered representative of the maximum acceptable departure from ideal approach conditions for the uncertainties given.

C.6 If approach conditions are unfavourable, strong secondary currents (spiral flow) may occur. Even though an isovel diagram showing forward components may appear reasonable in such circumstances, the presence of significant cross components of velocity would make such an installation unacceptable.

Annex D

Computation of discharge using boundary layer theory

D.1 General

Boundary layer theory can be used to determine the variations of the notional displacement of the flow boundaries, δ_* , and hence it is possible to use the more generalised expressions for C_D given in equations (24), (30) and (45).

D.2 Rectangular throated flume

D.2.1 The generalised expression for C_D , see equation (24), is :

$$C_D = \left(1 - 2 \frac{\delta_*}{L} \times \frac{L}{b}\right) \left(1 - \frac{\delta_*}{L} \times \frac{L}{h}\right)^{3/2} \dots (71)$$

D.2.2 The coefficient of discharge may be evaluated by equation (71) using the geometrical measurements of the structure, provided the boundary layer displacement thickness δ_* can be estimated. The relative boundary layer displacement thickness δ_*/L may be evaluated approximately from figure 13. In using this figure, certain simplifying assumptions are made :

- The boundary layer is assumed to originate at the leading edge of the prismatic portion of the throat.
- Transition from laminar to turbulent boundary layer is assumed to take place at a Reynolds number $Re = 3 \times 10^5$.
- The control section is presumed to be at the downstream end of the prismatic throat section.

D.2.3 The value of k_s , the equivalent sand grain roughness of the throat, may be selected from table 4 for a range of construction materials. From this, the ratio L/k_s may be computed.

D.2.4 The value of δ_*/L is insensitive to Re , but Re is dependent upon the discharge as follows :

$$Re \approx \frac{L}{\nu} \left(\frac{gQ}{b}\right)^{1/3} \dots (72)$$

Values of ν , the kinematic viscosity of water, are given in table 5.

D.2.5 The computation of discharge to the first approximation for a given head acting on a rectangular throated flume of known geometry is thus made as follows :

- List the values of b , B , p , L , g and k_s .
- Compute the area of the approach channel cross-section using equation (17).

c) Obtain the value of C_v from figure 6 assuming $\delta_* = 0$ and $C_v = 1.0$.

d) Make an approximation to Q using equation (20) and assuming $C_D = 1.00$.

e) Use equation (72) to obtain the Reynolds number Re .

f) Work out L/k_s and find δ_*/L from figure 13; hence δ_* .

g) Use equation (71) to compute C_D and recompute Q using equation (20).

D.2.6 Following the first approximation (in D.2.5) further approximations use steps c) to g) of D.2.5 as follows :

- Repeat using value of δ_* obtained in f) and equations (22) and (23) to determine $b_e h_e$.
- Repeat using value of δ_* obtained in f) and equations (21), (22) and (23) to determine C_D .
- Repeat as above.

D.3 Trapezoidal throated flumes

D.3.1 The generalised expression for C_D , see equation (30), is :

$$C_D = \left(1 - 2\eta \frac{\delta_*}{L} \times \frac{L}{b}\right) \left(1 - \frac{\delta_*}{L} \times \frac{L}{h}\right)^{3/2} \dots (73)$$

D.3.2 The coefficient of discharge may be evaluated from equation (73), using the geometrical measurements of the structure. The relative boundary layer displacement δ_*/L may be estimated from figure 13 (see D.2.2 for the simplifying assumptions implicit in figure 13).

D.3.3 The value of k_s , the equivalent sand roughness of the throat, may be selected from table 4 for a range of construction materials. From this the ratio L/k_s may be computed.

D.3.4 The value of δ_*/L is not very sensitive to Re , but this is dependent on the discharge, as follows :

$$Re = \frac{L}{\nu} \left(\frac{gQ}{b}\right)^{1/3} \left(\frac{b}{w_c}\right)^{1/3} \dots (74)$$

Values of ν for water are given in table 5. The ratio w_c/b is a function of mH_c/b , and, making the approximation $h = H_c$ for the purpose, may be read from figure 8.

D.3.5 The computation of discharge for a given head acting on a trapezoidal throated flume of known geometry is thus made as follows :

- List the values of m , m_a , b , B , p , L , g , ν and k_s .
- Compute the area of the approach channel cross-section. If it is of trapezoidal shape, use equation (18).
- As a first approximation, assume $mH_{ce}/b_e \approx mh/b$ and obtain C_s from figure 8 for the given value of h .
- Obtain a first approximation of C_v from figure 6 assuming $\delta_* = 0$.
- Obtain w_c/b from figure 14. As a first approximation, enter the diagram at the value of mh/b .
- Make an approximation to Q using equation (29) with the above values of C_v , C_s and assuming $C_D = 1.00$.
- Use equation (74) to obtain the Reynolds number, Re .
- Work out L/k_s and find δ_*/L from figure 13; hence δ_* .
- $\eta = \sqrt{(1 + m^2)} - m$, or obtain from figure 7.
- Use equation (73) to compute C_D , and recompute Q (equation 29) using this value.

D.3.6 This completes the first approximation. These values of C , C_v , C_D and Q are utilized in beginning the second approximation as follows :

- mH_{ce}/b_e is obtained from equation (32).
- Figure 8 is used with the above to obtain a close approximation of C_s .
- $C_s b_e h_e/A$ can now be worked out, and a new value of C_v obtained from figure 6.
- The value of C_D , together with the revised values of C_v and C_s , shall then be inserted in equation (29) to obtain a more accurate figure for Q .

D.3.7 Steps a) to d) shall be repeated until sufficient precision has been obtained in the values of C_s , C_v and C_D . As C_D is relatively insensitive to Re , it is seldom necessary to go beyond the first approximation to Re , but third or fourth applications of steps a) to c) may be necessary.

D.4 U-throated (round-bottomed) flumes

D.4.1 The generalised expression for C_D , see equation (45), is :

$$C_D = \left(1 - 2 \frac{\delta_*}{L} \times \frac{L}{D}\right) \left(1 - \frac{\delta_*}{L} \times \frac{L}{h}\right)^{3/2} \quad \dots (75)$$

D.4.2 The coefficient of discharge C_D may be evaluated by equation (75), using the geometrical measurements of the structure. It is first necessary to evaluate the relative boundary layer displacement δ_*/L . This may be estimated from figure 13 (see D.2.2 for the simplifying assumptions implicit in figure 13) where it is expressed as a function of relative roughness L/k_s and Reynolds number Re .

D.4.3 The value of k_s , the equivalent sand roughness of the throat, may be selected from table 4 for a range of construction materials. From this and the throat length, L , the ratio L/k_s may be computed.

D.4.4 The value of δ_*/L is not very sensitive to Reynolds number, but Re is dependent on the discharge, as follows :

$$Re \approx \frac{L}{\nu} \left(\frac{gQ}{D}\right)^{1/3} \left(\frac{D}{w_c}\right)^{1/3} \quad \dots (76)$$

An alternative expression in terms of the gauged head, h , is more convenient :

$$Re \approx \frac{L}{\nu} \sqrt{\frac{2}{3} gh} (C_v C_u C_D)^{1/3} \left(\frac{D}{w_c}\right)^{1/3} \quad \dots (77)$$

The first approximations to C_u and C_v obtained as suggested in 12.4.3 and 12.4.4, and the assumption $C_D \approx 1$, may be utilized in evaluating equation (77).

Values of w_c/D are shown in figure 15 against H_c/D . In reading off the value of w_c/D to insert in equation (77), the approximation $h = H_c$ may be made.

D.4.5 The computation of discharge for a given head acting on a U-shaped flume of known geometry thus proceeds as follows :

- List the values of D , L , D_a , p , k_s and ν .
- Compute the area of the approach channel cross-section; if it is of U-shape, use equation (19).
- As a first approximation, assume $H_{ce}/D_e \approx h/D$ and obtain C_u from figure 10 for the given value of h .
- Obtain a first approximation of C_v from figure 6, assuming $\delta_* = 0$.
- Evaluate $\sqrt{(2gh/3)}$, L/ν , and L/k_s .
- Obtain w_c/D from figure 15, again using as a first approximation $H_c/D \approx h/D$.
- Estimate Reynolds number from equation (77), assuming $C_D = 1.0$.
- Read from figure 13 the value of δ_*/L corresponding to these values of L/k_s and Re .
- Evaluate L/D and L/h and compute C_D from equation (75).
- H_{ce} can be estimated from equation (47) using the above values of h , δ_*/L , L and C_v . D_e is obtained from $D_e = D - 2\delta_*$ and h_e is obtained from $h_e = h - \delta_*$.

D.4.6 This completes the first approximation. These values of H_{ce} , C_v and C_D are utilized in beginning the second approximation, as follows :

- a) Evaluate H_{ce}/D_e and obtain a revised value of C_u from figure 10.
- b) Evaluate $C_u D_e h_e/A$ and obtain a revised value of C_v from figure 6.
- c) Obtain a revised estimate of H_{ce} from equation (47), using the revised value of C_v .

D.4.7 Steps a) to c) shall be repeated until sufficient precision has been obtained in the values of C_u and C_v . As δ_*/L is relatively insensitive to Re , it is not usually necessary to go beyond the first approximation to Re , but third or fourth applications of steps a) to c) may be necessary.

D.4.8 Discharge is then computed from equation (44) for the given head.

Annex E

Examples illustrating methods for the computation of discharge

E.1 Calculation of single discharge for a trapezoidal throated flume

$$\frac{\delta_*}{L} = 0,003$$

E.1.1 $m = m_a = 1,00$ $p = 0,15 \text{ m}$ $g = 9,81 \text{ m/s}^2$
 $b = 0,50 \text{ m}$ $L = 3,00 \text{ m}$ $h = 1,00 \text{ m}$
 $B = 2,00 \text{ m}$

E.1.2 Using the method described in 11.4, the calculation proceeds as follows :

Parameter	Approximation			Equation or figure used
	first	second	third	
Area of approach channel, $A \text{ (m}^2\text{)}$	3,968	—	—	Equation 18
Numerical coefficient, η	0,414 2	—	—	Figure 7
Coefficient of discharge, C_D	0,971 8	—	—	Equation 31
mH_{ce}/b_e	2,000	2,030	2,031	—
Shape coefficient, C_s	2,435	2,445	2,450	Figure 8
$C_s b_e h_e/A$	0,306 9	0,308 1	0,308 8	—
Coefficient of velocity, C_v	1,023	1,023	1,023	Figure 6
Discharge, $Q \text{ (m}^3\text{/s)}$	2,062	2,072	2,076	Equation 29

E.2 Calculation of single discharge for a trapezoidal throated flume; boundary layer corrections

E.2.1 $m = m_a = 1,00$ $p = 0,15 \text{ m}$ $\nu = 1,141 \times 10^{-6} \text{ m}^2\text{/s}$
 $b = 0,50 \text{ m}$ $L = 3,00 \text{ m}$ $k_s = 0,001 5 \text{ m}$
 $B = 2,00 \text{ m}$ $g = 9,81 \text{ m/s}^2$ $h = 1,00 \text{ m}$

E.2.2 Using the method described in annex D, the calculation proceeds as follows :

Parameter	Approximation			Equation or figure used
	first	second	third	
Area of approach channel, $A \text{ (m}^2\text{)}$	3,968	—	—	Equation 18
mH_{ce}/b_e	2,000	2,030	2,031	—
Shape coefficient, C_s	2,435	2,445	2,450	Figure 8
$C_s b_e h_e/A$	0,306 9	0,308 1	0,308 8	—
Coefficient of velocity, C_v	1,023	1,023	1,023	Figure 6
w_c/b	4,1	—	—	Figure 14
Discharge, $Q \text{ (m}^3\text{/s)}$	2,123	2,029	2,033	Equation 29
Reynolds number, Re	$5,69 \times 10^6$	—	—	Equation 74
δ_*/L	0,005 2	—	—	Figure 13
$\delta_* \text{ (m)}$	0,015 6	—	—	—
Numerical coefficient, η	0,414 2	—	—	Figure 7
Coefficient of discharge, C_D	0,951 5	—	—	Equation 73
Discharge, $Q \text{ (m}^3\text{/s)}$	2,019	—	—	Equation 29

E.3 Calculation of stage-discharge curve for trapezoidal flume

$$\delta_*/L = 0,003$$

E.3.1 $m = m_a = 1,00$ $B = 2,00$ m $L = 3,00$ m
 $b = 0,50$ m $p = 0,15$ m $g = 9,81$ m/s²

E.3.2 Example of calculation of stage-discharge curve for a trapezoidal-throated flume when $\delta_*/L = 0,003$.

Variables	d_c	w_c	P_c	A_c	Q	H_e	H_*	H	$\bar{v}_{a1}$	h_1	$\bar{v}_{a2}$	h_2	$\bar{v}_{a3}$	h_3
How obtained	Input	Equation (34)	Equation (37)	Equation (35)	Equation (13)	Equation (14)	Equation (36)	$(H_* + H_e)$	Equation (39) and $\bar{v}_{a1} = Q/A_{a1}$ with $h = H$	Equation (38) ($\bar{v}_a = \bar{v}_{a1}$)	Equation (39) and $\bar{v}_{a2} = Q/A_{a2}$ with $h = h_1$	Equation (38) ($\bar{v}_a = \bar{v}_{a2}$)	Equation (39) and $\bar{v}_{a3} = Q/A_{a3}$ with $h = h_2$	Equation (38) ($\bar{v}_{a1} = \bar{v}_{a2}$)
	m	m	m	m ²	m ³ /s	m	m	m	m/s	m	m/s	m	m/s	m
Results	0,10	0,700	0,783	0,060	0,055	0,142 8	0,010 1	0,152 9	0,078 9	0,152 6	0,078 9	0,152 6	0,078 9	0,152 6
	0,20	0,900	1,066	0,140	0,173	0,277 8	0,010 6	0,288 4	0,161 8	0,287 1	0,162 4	0,287 1	0,162 4	0,287 1
	0,40	1,300	1,631	0,360	0,593	0,538 5	0,011 3	0,549 8	0,313 9	0,544 8	0,316 7	0,544 7	0,316 8	0,544 7
	0,60	1,700	2,197	0,660	1,288	0,794 1	0,011 6	0,805 7	0,456 0	0,795 1	0,462 7	0,794 8	0,462 9	0,794 8
	0,80	2,100	2,763	1,040	2,292	1,047 6	0,011 8	1,059 4	0,590 5	1,041 6	0,602 7	1,040 9	0,603 2	1,040 9
	1,00	2,500	3,328	1,500	3,639	1,300 0	0,011 9	1,311 9	0,719 0	1,285 6	0,737 8	1,284 1	0,738 9	1,284 1
	1,50	3,500	4,743	3,000	8,699	1,928 6	0,012 2	1,940 8	1,017 1	1,888 1	1,057 0	1,883 9	1,060 3	1,883 5
	2,00	4,500	6,157	5,000	16,508	2,555 6	0,012 3	2,567 9	1,287 5	2,483 4	1,352 9	2,474 6	1,360 0	2,473 6

E.4 Calculation of stage-discharge curve for trapezoidal throated flume; boundary layer corrections

E.4.1 $m = m_a = 1,00$ $p = 0,15$ m $\nu = 1,141 \times 10^{-6}$ m²/s
 $b = 0,50$ m $L = 3,00$ m $k_s = 0,001$ 5
 $B = 2,00$ m $g = 9,81$ m/s²

E.4.2 Example of calculation of stage-discharge curve for a trapezoidal-throated flume with boundary layer corrections.

Variables	d_c	w_c	P_c	A_c	Q	H_e	Re	δ_*/L	H_*	H	$\bar{v}_{a1}$	h_1	$\bar{v}_{a2}$	h_2	$\bar{v}_{a3}$	h_3
How obtained	Input	Equation (34)	Equation (37)	Equation (35)	Equation (13)	Equation (14)		Figure 13 ($L/k_s = 2\ 000$)	Equation (36)	$(H_* + H_e)$	Equation (39) and $\bar{v}_{a1} = Q/A_{a1}$ with $h = H$	Equation (38) ($\bar{v}_a = \bar{v}_{a1}$)	Equation (39) and $\bar{v}_{a2} = Q/A_{a2}$ with $h = h_1$	Equation (38) ($\bar{v}_a = \bar{v}_{a2}$)	Equation (39) and $\bar{v}_{a3} = Q/A_{a3}$ with $h = h_2$	Equation (38) ($\bar{v}_{a1} = \bar{v}_{a2}$)
	m	m	m	m ²	m ³ /s	m			m	m	m/s	m	m/s	m	m/s	m
Results	0,20	0,900	1,066	0,140	0,173	0,277 8	$3,25 \times 10^6$	0,005 0	0,017 7	0,295 5	0,158 8	0,294 2	0,159 3	0,294 3	0,159 3	0,294 3
	0,60	1,700	2,197	0,660	1,288	0,794 1	$5,13 \times 10^6$	0,005 1	0,019 8	0,813 9	0,450 8	0,803 5	0,457 4	0,803 2	0,457 6	0,803 2
	1,00	2,500	3,328	1,500	3,639	1,300 0	$6,38 \times 10^6$	0,005 2	0,020 8	1,320 8	0,712 9	1,294 9	0,731 1	1,293 6	0,732 0	1,293 5
	1,50	3,500	4,743	3,000	8,699	1,928 6	$7,62 \times 10^6$	0,005 2	0,021 1	1,949 7	1,010 6	1,897 6	1,849 6	1,893 6	1,052 7	1,893 2
	2,00	4,500	6,157	5,000	16,508	2,555 6	$8,68 \times 10^6$	0,005 2	0,021 3	2,576 9	1,280 7	2,493 3	1,345 0	2,484 7	1,351 9	2,483 7

E.5 Calculation of single discharge for a U-throated flume; $\delta_*/L = 0,003$

E.5.1 $D = 0,40 \text{ m}$ $D_a = 0,60 \text{ m}$ $g = 9,81 \text{ m/s}^2$
 $L = 1,00 \text{ m}$ $p = 0,0$ $h = 0,25 \text{ m}$

E.5.2 Using the method described in 12.4, the calculation proceeds as follows :

Parameter	Approximation			Equation or figure used
	first	second	third	
Area of approach channel, $A \text{ (m}^2\text{)}$	0,111 5	—	—	Equation 49
H_{ce}/D_e	0,625 0	0,679 3	0,683 4	—
Shape coefficient, C_u	0,754	0,776	0,777	Figure 10
$C_u D h/A$	0,676 2	0,695 9	0,696 8	—
Coefficient of velocity, C_v	1,133	1,144	1,144	Figure 6
Coefficient of discharge, C_D	0,967 3	—	—	Equation 46
Effective total head, $H_{ce} \text{ (m)}$	0,271 7	0,273 4	0,273 4	Equation 48
Discharge, $Q \text{ (m}^3\text{/s)}$	—	—	0,073 6	Equation 44

E.6 Calculation of single discharge for a U-throated flume; boundary layer corrections

E.6.1 $D = 0,40 \text{ m}$ $p = 0,0$ $k_s = 0,000 6 \text{ m}$
 $L = 1,00 \text{ m}$ $g = 9,81 \text{ m/s}^2$ $h = 0,25 \text{ m}$
 $D_a = 0,60 \text{ m}$ $\nu = 1,141 \times 10^{-6} \text{ m}^2/\text{s}$

E.6.2 Using the method described in annex D, the calculation proceeds as follows :

Parameter	Approximation			Equation or figure used
	first	second	third	
Area of approach channel, $A \text{ (m}^2\text{)}$	0,111 5	—	—	Equation 19
H_{ce}/D_e	0,625 0	0,682 5	0,680 5	—
Shape coefficient, C_u	0,754	0,778	0,778	Figure 10
$C_u D h/A$	0,676 2	0,697 8	0,697 8	—
Coefficient of velocity, C_v	1,133	1,145	1,145	Figure 6
w_c/D	0,993	—	—	Figure 15
Reynolds number, Re	$1,06 \times 10^6$	—	—	Equation 77
δ_*/L	0,004 7	—	—	Figure 13
$\delta_* \text{ (m)}$	0,004 7	—	—	—
Coefficient of discharge, C_D	0,949 1	—	—	Equation 75
Effective total head, $H_{ce} \text{ (m)}$	0,266 6	0,268 5	0,268 5	Equation 47
Discharge, $Q \text{ (m}^3\text{/s)}$	—	—	0,072 07	Equation 44

E.7 Calculation of stage-discharge curve for a U-shape throated flume

$$\delta_s/L = 0,003$$

E.7.1 $D = 0,40 \text{ m}$ $D_a = 0,60 \text{ m}$ $g = 9,81 \text{ m/s}^2$
 $L = 1,00 \text{ m}$ $p = 0,0$

E.7.2 Example of calculation of stage-discharge curve for a U-throated flume when $\delta_s/L = 0,003$

Variables	θ_{throat}	d_c	w_c	P_c	A_c	Q	H_e	H_s	H	$\bar{v}_{a1}$	h_1	$\bar{v}_{a2}$	h_2	$\bar{v}_{a3}$	h_3
How obtained	Input	Equation (52) (or input)	Equation (53) or (55)	Equation (58) or (59)	Equation (54) or (56)	Equation (13)	Equation (14)	Equation (57)	$(H_e + H_s)$	Equation (61) or (62) and $\bar{v}_{a1} = Q/A_{a1}$ with $h = H$	Equation (60) ($\bar{v}_a = \bar{v}_{a1}$)	Equation (61) or (62) and $\bar{v}_{a2} = Q/A_{a2}$ with $h = h_1$	Equation (60) ($\bar{v}_a = \bar{v}_{a2}$)	Equation (61) or (62) and $\bar{v}_{a3} = Q/A_{a3}$ with $h = h_2$	Equation (60) ($\bar{v}_a = \bar{v}_{a3}$)
Results	rad	m	m	m	m	m ³ /s	m	m	m	m/s	m	m/s	m	m/s	m
	1,00	0,091 9	0,336 6	0,400 0	0,021 8	0,017 4	0,124 3	0,003 6	0,127 9	0,394 6	0,120 0	0,431 8	0,118 4	0,440 5	0,118 0
	1,30	0,146 5	0,385 4	0,520 0	0,041 7	0,043 0	0,200 6	0,004 0	0,204 6	0,505 3	0,191 6	0,552 7	0,189 0	0,563 6	0,188 4
	$\pi/2$	0,200 0	0,400 0	0,628 6	0,062 8	0,077 9	0,278 5	0,004 7	0,283 2	0,593 3	0,265 3	0,645 9	0,261 9	0,656 8	0,261 2
		0,250 0	0,400 0	0,728 3	0,082 8	0,118 0	0,353 3	0,005 5	0,359 0	0,667 4	0,336 3	0,723 0	0,332 4	0,733 8	0,331 6
		0,300 0	0,400 0	0,828 3	0,102 8	0,163 2	0,428 5	0,006 2	0,434 7	0,734 5	0,407 2	0,793 4	0,402 6	0,803 9	0,401 8
		0,400 0	0,400 0	1,028 3	0,142 8	0,267 2	0,578 5	0,007 7	0,586 2	0,853 4	0,549 1	0,918 5	0,543 2	0,930 0	0,542 1

E.8 Calculation of stage-discharge curve for a U-throated flume; boundary layer corrections

E.8.1 $D = 0,40 \text{ m}$ $p = 0,0$ $\nu = 1,141 \times 10^{-6} \text{ m}^2/\text{s}$
 $L = 1,00 \text{ m}$ $g = 9,81 \text{ m/s}^2$ $k_s = 0,000 6 \text{ m}$
 $D_a = 0,60 \text{ m}$

E.8.2 Example of calculation of stage-discharge curve for a U-throated flume with boundary layer correction.

Variables	θ_{throat}	d_c	w_c	P_c	A_c	Q	H_e	Re	δ_s/L	H_s	H	$\bar{v}_{a1}$	h_1	$\bar{v}_{a2}$	h_2	$\bar{v}_{a3}$	h_3
How obtained	Input	Equation (52) (or input)	Equation (53) or (55)	Equation (58) or (59)	Equation (54) or (56)	Equation (13)	Equation (14)	Equation (76)	Figure 13 ($L/k_s = 1\ 667$)	Equation (57)	$(H_e + H_s)$	Equation (61) or (62) and $\bar{v}_{a1} = Q/A_{a1}$ with $h = H$	Equation (60) ($\bar{v}_a = \bar{v}_{a1}$)	Equation (61) or (62) and $\bar{v}_{a2} = Q/A_{a2}$ with $h = h_1$	Equation (60) ($\bar{v}_a = \bar{v}_{a2}$)	Equation (61) or (62) and $\bar{v}_{a3} = Q/A_{a3}$ with $h = h_2$	Equation (60) ($\bar{v}_a = \bar{v}_{a3}$)
Results	rad	m	m	m	m	m ³ /s	m			m	m	m/s	m	m/s	m	m/s	m
	1,00	0,091 9	0,336 6	0,400 0	0,021 8	0,017 4	0,124 3	$6,99 \times 10^5$	0,004 0	0,004 8	0,129 1	0,389 3	0,121 4	0,425 1	0,119 9	0,432 7	0,119 6
	$\pi/2$	0,200 0	0,400 0	0,628 3	0,062 8	0,077 9	0,278 5	$1,09 \times 10^6$	0,004 7	0,007 4	0,285 9	0,586 2	0,268 4	0,635 9	0,265 3	0,645 9	0,264 6
	—	0,300 0	0,400 0	0,828 3	0,102 8	0,163 2	0,428 5	$1,39 \times 10^6$	0,005 0	0,010 4	0,438 9	0,726 3	0,412 0	0,782 4	0,407 7	0,792 2	0,406 9
	—	0,400 0	0,400 0	1,028 3	0,142 8	0,267 2	0,578 5	$1,64 \times 10^6$	0,005 2	0,013 4	0,591 9	0,844 2	0,555 6	0,906 4	0,550 0	0,917 0	0,549 0

Annex F

Example of the computation of the overall uncertainty of discharge measurement

F.1 The following is an example of the application of the uncertainty formula. In each case the component uncertainties (X_c , X_b , X_h and X_m) may be taken as percentage standard deviations at the 95 % confidence level. The total uncertainty X therefore is found with 95 % confidence. It is assumed in the example that the head is measured by digital punched tape recorder having a resolution of 1 mm with an uncertainty of ± 3 mm (ε_h). The zero is measured in each case to ± 1 mm (ε_z).

It is assumed in the example that a series of readings of a constant head produced a standard deviation of the mean of 1,5 mm.

F.2 Rectangular throated flume with a throat width b of 1,0 m, approach channel width B of 2,0 m, hump height p of 0,25 m and a throat length L of 3,0 m. The uncertainty in width may be taken as ± 2 mm.

F.3 The overall uncertainty in discharge at a given head, say 1,00 m, is calculated as follows :

h	= 1,00 m
b/B	= 0,5
$h/(h + p)$	= 0,80
C_v	= 1,039, from table 2
h/L	= 0,33
L/b	= 3,0
C_D	= 0,968, from table 1

Hence

$$\begin{aligned}
 X_C &= \pm 2,4 \% \text{ using equation (28)} \\
 X_h &= \pm 0,44 \% \text{ using equation (70)} \\
 X_b &= \pm 0,2 \% \text{ using equation (69)} \\
 X &= \pm (2,4^2 + 0,2^2 + 1,5^2 \times 0,44^2)^{1/2} \\
 &= \pm 2,5 \%
 \end{aligned}$$

Annex G

Determination of height of hump — Rectangular throated flumes

G.1 Stage-discharge relation

The stage-discharge relation of a channel or distributory is given by

$$Q = C_1 d_a^z \quad \dots (78)$$

where

Q is the discharge;

C_1 is a coefficient;

d is the central depth of water in the channel;

z is the index which varies between 1,5 and 2,0.

Values of z are summarised below :

Series number	Shape of channel	z
1	Rectangular	1,5
2	Trapezoidal	Variable and increases with the flatness of the side slope
3	Unlined channels with design side slopes 1/2 to 1	1,6 to 1,7
4	Lined channels with slopes 1,5 to 1	1,9 to 2,0

As compared to the above equation, the discharge in the case of a broad crested weir is proportional to $H^{1,5}$ and also to $h^{1,5}$ where H and h are the total and gauged heads respectively. As the exponent of d_a^z is greater than the exponent of h , there will be draw-down at low flows and ponding at high flows provided the sill of the throat is at the same level of the channel bed. Draw-down could result in scour and ponding in silting. This can be avoided by providing a hump in the flume throat. The height of hump " p " required to give proportionality i.e. rate of change in " d_a " equal to the rate of change in " h " at a particular discharge thus ensuring absence of either draw-down or ponding is worked out below.

G.1.1 Proportionality for a small variation from a particular discharge

$$Q = C_1 d_a^z \quad (\text{for channel}) \quad \dots (79)$$

$$= C_D h^{1,5} \quad (\text{for flume}) \quad \dots (80)$$

Since the rate of change of discharge in the approach channel (d_a in channel) is equal to the rate of change over the flume (h in flume)

$$z C_1 d_a^{z-1} = 1,5 C_D \times h^{0,5} \quad \dots (81)$$

substituting C_1 and C_D from equations (79) and (80) into (81)

$$z \frac{Q}{d_a^z} \times d_a^{z-1} = 1,5 \frac{Q}{h^{1,5}} \times h^{0,5} \quad \dots (82)$$

simplifying

$$\frac{z}{d_a} = \frac{3}{2} \times \frac{1}{h} \quad \dots (83)$$

hence

$$h = \frac{3}{2} \times \frac{d_a}{z} \quad \dots (84)$$

Similarly any fraction of discharge say

$$JQ = C_1 d_{aJ}^z \quad \dots (85)$$

$$JC_1 d_a^z = C_1 d_{aJ}^z \quad \dots (86)$$

Hence

$$d_a J^{1/z} = d_{aJ} \quad \text{for channel} \quad \dots (87)$$

on the same lines

$$h_J = h \times J^{2/3} \quad \dots (88)$$

Therefore height of hump

$$p = d_J - h_J \quad \dots (89)$$

$$= d_a J^{1/z} - h J^{2/3} \quad \dots (90)$$

Substituting value of h from equation (84) into equation (90)

Height of hump :

$$p = d_a J^{1/z} - \frac{3}{2} \times \frac{d_a}{z} \times J^{2/3} \quad \dots (91)$$

$$p = d_a \left(J^{1/z} - \frac{3}{2} \times \frac{J^{2/3}}{z} \right) \quad \dots (92)$$

Figure 16 gives the height of hump required to give proportionality at a particular value of J .

G.1.2 For bulk proportionality

Where channels are run with fluctuating discharge, the proportionality is not obtainable for the whole range and it is then desirable to design the hump such that error over the range of discharges chosen will be minimum. This is called the "bulk

proportionality" and in this case the height of hump required to obtain bulk proportionality for Q_1 to Q_2 is evaluated as given below

$$Q_1 = C_1 d_{a1}^z = C_D h_1^{1.5} \quad \dots (93)$$

and

$$Q_2 = JQ_1 = C_1 d_{a2}^z = C_D h_2^{1.5} \quad \dots (94)$$

Therefore

$$d_{a1} = \frac{1}{J^{1/z}} \times d_{a2} \text{ and } h_1 = \frac{1}{J^{2/3}} \times h_2 \quad \dots (95)$$

For bulk proportionality

$$d_{a1} - d_{a2} = h_1 - h_2 \quad \dots (96)$$

Hence

$$\frac{1}{J^{1/z}} \times d_{a2} - d_{a2} = \frac{1}{J^{2/3}} \times h_2 - h_2 \quad \dots (97)$$

Therefore

$$d_{a2} \left(\frac{1}{J^{1/z}} - 1 \right) = \left(\frac{1}{J^{2/3}} - 1 \right) h_2 \quad \dots (98)$$

Hence

$$h_2 = \frac{d_{a2} \left(\frac{1}{J^{1/z}} - 1 \right)}{\left(\frac{1}{J^{2/3}} - 1 \right)} \quad \dots (99)$$

Height of hump :

$$p = d_{a2} - h_2 \quad \dots (100)$$

Substituting value of h_2 from equation (99)

Height of hump :

$$\begin{aligned} p &= d_{a2} - d_{a2} \left[\frac{\left(\frac{1}{J^{1/z}} - 1 \right)}{\left(\frac{1}{J^{2/3}} - 1 \right)} \right] \\ &= d_{a2} \left[1 - \frac{\left(\frac{1}{J^{1/z}} - 1 \right)}{\left(\frac{1}{J^{2/3}} - 1 \right)} \right] \quad \dots (101) \end{aligned}$$

Substituting d_{a2} by d_{a1} and J , from equation (95)

Height of hump :

$$p = d_{a1} J^{1/z} \left[1 - \frac{\left(\frac{1}{J^{1/z}} - 1 \right)}{\left(\frac{1}{J^{2/3}} - 1 \right)} \right] \quad \dots (102)$$

Figure 17 gives the height of hump required for various values of z and fluctuations in discharges i.e. J .

Table 1 — Discharge coefficients for rectangular throated flumes

$$C_D = \left(1 - \frac{0,006 L}{b}\right) \left(1 - \frac{0,003 L}{h}\right)^{3/2}$$

$\frac{L}{b}$	$\frac{h}{L}$													
	0,70	0,65	0,60	0,55	0,50	0,45	0,40	0,35	0,30	0,25	0,20	0,15	0,10	0,05
0,2	0,992 4	0,991 9	0,991 3	0,990 6	0,989 8	0,988 8	0,987 6	0,986 0	0,983 9	0,980 9	0,976 4	0,969 0	0,954 2	0,910 3
0,4	0,991 2	0,990 7	0,990 1	0,989 4	0,988 6	0,987 6	0,986 4	0,984 8	0,982 7	0,979 7	0,975 2	0,967 8	0,953 0	0,909 2
0,6	0,990 0	0,989 5	0,988 9	0,988 3	0,987 5	0,986 5	0,985 2	0,983 6	0,981 5	0,978 5	0,974 1	0,966 7	0,951 9	0,908 1
0,8	0,988 8	0,988 3	0,987 8	0,987 1	0,986 3	0,985 3	0,984 0	0,982 5	0,980 3	0,977 4	0,972 9	0,965 5	0,950 2	0,907 0
1,0	0,987 6	0,987 2	0,986 6	0,985 9	0,985 1	0,984 1	0,982 9	0,981 3	0,979 2	0,976 2	0,971 7	0,964 4	0,949 6	0,905 9
1,2	0,986 5	0,986 0	0,985 4	0,984 7	0,983 9	0,982 9	0,981 7	0,980 1	0,978 0	0,975 0	0,970 6	0,963 2	0,948 5	0,904 8
1,4	0,985 3	0,984 8	0,984 2	0,983 5	0,982 7	0,981 8	0,980 5	0,978 9	0,976 8	0,973 9	0,969 4	0,962 0	0,947 4	0,903 8
1,6	0,984 1	0,983 6	0,983 1	0,982 4	0,981 6	0,980 6	0,979 3	0,977 8	0,975 7	0,972 7	0,968 3	0,960 9	0,946 2	0,902 7
1,8	0,982 9	0,982 4	0,981 9	0,981 2	0,980 4	0,979 4	0,978 2	0,976 6	0,974 5	0,971 5	0,967 1	0,959 8	0,945 1	0,901 6
2,0	0,981 8	0,981 3	0,980 7	0,980 0	0,979 2	0,978 2	0,977 0	0,975 4	0,973 3	0,970 4	0,966 0	0,958 6	0,944 0	0,900 5
2,2	0,980 6	0,980 1	0,979 5	0,978 9	0,978 1	0,977 1	0,975 8	0,974 3	0,972 2	0,969 2	0,964 8	0,957 5	0,942 9	0,899 5
2,4	0,979 4	0,978 7	0,978 4	0,977 7	0,976 9	0,975 9	0,974 7	0,973 1	0,971 0	0,968 1	0,963 7	0,956 3	0,941 7	0,898 4
2,6	0,978 3	0,977 8	0,977 2	0,976 5	0,975 7	0,974 8	0,973 5	0,972 0	0,969 9	0,966 9	0,962 5	0,955 2	0,940 6	0,897 3
2,8	0,977 1	0,976 6	0,976 1	0,975 4	0,974 6	0,973 6	0,972 4	0,970 8	0,968 7	0,965 8	0,961 4	0,954 1	0,939 5	0,896 3
3,0	0,975 9	0,975 5	0,974 9	0,974 2	0,973 4	0,972 4	0,971 2	0,969 6	0,967 6	0,964 6	0,960 2	0,952 9	0,938 4	0,895 2
3,2	0,974 8	0,974 3	0,973 3	0,973 1	0,972 3	0,971 3	0,970 1	0,968 5	0,966 4	0,963 5	0,959 1	0,951 8	0,937 3	0,894 1
3,4	0,973 6	0,973 1	0,972 6	0,971 9	0,971 1	0,970 1	0,968 9	0,967 3	0,965 3	0,962 3	0,958 0	0,950 7	0,936 2	0,893 1
3,6	0,972 5	0,972 0	0,971 4	0,970 8	0,970 0	0,969 0	0,967 8	0,966 2	0,964 1	0,961 2	0,956 8	0,949 5	0,935 0	0,892 0
3,8	0,971 3	0,970 8	0,970 3	0,969 6	0,968 8	0,967 8	0,966 6	0,965 1	0,963 0	0,960 1	0,955 7	0,948 4	0,933 9	0,890 9
4,0	0,970 2	0,969 7	0,969 1	0,968 5	0,967 7	0,966 7	0,965 5	0,963 9	0,961 8	0,958 9	0,954 6	0,947 3	0,932 8	0,889 9
4,2	0,969 0	0,968 5	0,968 0	0,967 3	0,966 5	0,965 6	0,964 3	0,962 8	0,960 7	0,957 8	0,953 4	0,946 2	0,931 7	0,888 8
4,4	0,967 9	0,967 4	0,966 8	0,966 2	0,965 4	0,964 4	0,963 2	0,961 6	0,959 6	0,956 6	0,952 3	0,945 1	0,930 6	0,887 8
4,6	0,966 7	0,966 3	0,965 7	0,965 0	0,964 2	0,963 3	0,962 1	0,960 5	0,958 4	0,955 5	0,951 2	0,943 9	0,929 5	0,886 7
4,8	0,965 6	0,965 1	0,964 6	0,963 9	0,963 1	0,962 1	0,960 9	0,959 4	0,957 3	0,954 4	0,950 0	0,942 8	0,928 4	0,885 7
5,0	0,964 5	0,964 0	0,963 4	0,962 8	0,962 0	0,961 0	0,959 3	0,958 3	0,956 2	0,953 3	0,949 0	0,941 8	0,927 4	0,884 7

NOTE — The number of significant figures given in the columns for coefficient of discharge should not be taken to imply a corresponding accuracy but only to assist in interpolation and analysis.

Table 2 — Velocity coefficients for rectangular throated flumes

$$\frac{4}{27} \left(\frac{b}{B}\right)^2 \left(\frac{h}{h+p}\right)^2 C_b^2 C_v^2 - C_v^{2/3} + 1 = 0$$

$\frac{b}{B}$	$\frac{h}{h+p} C_D$								
	1,0	0,9	0,8	0,7	0,6	0,5	0,4	0,3	0,2
0,10	1,002 2	1,001 8	1,001 4	1,001 1	1,000 8	1,000 6	1,000 4	1,000 2	1,000 1
0,15	1,005 1	1,004 1	1,003 2	1,002 5	1,001 8	1,001 3	1,000 8	1,000 5	1,000 2
0,20	1,009 1	1,007 3	1,005 8	1,004 4	1,003 2	1,002 2	1,001 4	1,000 8	1,000 4
0,25	1,014 3	1,011 5	1,009 1	1,006 9	1,005 1	1,003 5	1,002 2	1,001 3	1,000 6
0,30	1,020 9	1,016 8	1,013 2	1,010 0	1,007 3	1,005 1	1,003 2	1,001 8	1,000 8
0,35	1,029 0	1,023 2	1,018 1	1,013 7	1,010 0	1,006 9	1,004 4	1,002 5	1,001 1
0,40	1,038 6	1,030 8	1,024 0	1,018 1	1,013 2	1,009 1	1,005 8	1,003 2	1,001 4
0,45	1,050 0	1,039 7	1,030 8	1,023 2	1,016 8	1,011 5	1,007 3	1,004 1	1,001 8
0,50	1,063 5	1,050 0	1,038 6	1,029 0	1,020 9	1,014 3	1,009 1	1,005 1	1,002 2
0,55	1,079 3	1,062 0	1,047 6	1,035 7	1,025 5	1,017 5	1,011 0	1,006 1	1,002 7
0,60	1,098 0	1,076 0	1,057 9	1,042 9	1,030 8	1,020 9	1,013 2	1,007 3	1,003 2
0,65	1,120 3	1,092 1	1,069 5	1,051 3	1,036 7	1,024 8	1,015 6	1,008 6	1,003 8
0,70	1,146 5	1,110 8	1,082 9	1,060 6	1,042 9	1,029 0	1,018 1	1,010 0	1,004 4
0,75		1,132 7	1,098 0	1,071 1	1,050 0	1,033 6	1,020 9	1,011 5	1,005 1
0,80			1,115 3	1,082 9	1,057 9	1,038 6	1,024 0	1,013 2	1,005 8
0,85			1,135 3	1,096 0	1,066 4	1,044 1	1,027 2	1,014 9	1,006 5
0,90				1,110 8	1,076 0	1,050 0	1,030 8	1,016 8	1,007 3
0,95				1,127 5	1,086 4	1,056 4	1,034 6	1,018 8	1,008 2
1,00				1,146 5	1,098 0	1,063 5	1,038 6	1,020 9	1,009 1

NOTE — The number of significant figures given in the columns for coefficient of velocity should not be taken to imply a corresponding accuracy but only to assist in interpolation and analysis.

Table 3 — Circular functions for use in
deriving calibration of U-throated flumes

θ rad	$f_1(\theta)$	$f_2(\theta)$	$f_3(\theta)$
0,5	0,061 21	0,479 4	0,019 62
0,6	0,087 33	0,564 6	0,033 49
0,7	0,117 6	0,644 2	0,051 82
0,8	0,151 6	0,717 4	0,075 05
0,9	0,189 2	0,783 3	0,103 3
1,0	0,229 8	0,841 5	0,136 3
1,1	0,273 2	0,891 2	0,173 9
1,2	0,318 8	0,932 0	0,215 6
1,3	0,366 2	0,963 6	0,260 6
1,4	0,415 0	0,985 4	0,308 1
1,5	0,464 6	0,997 5	0,357 4
$\pi/2$	0,500 0	1,000 0	0,392 7

$f_1(\theta) = 1/2 (1 - \cos \theta)$

$f_2(\theta) = \sin \theta$

$f_3(\theta) = 1/4 (\theta - \sin \theta \cos \theta)$

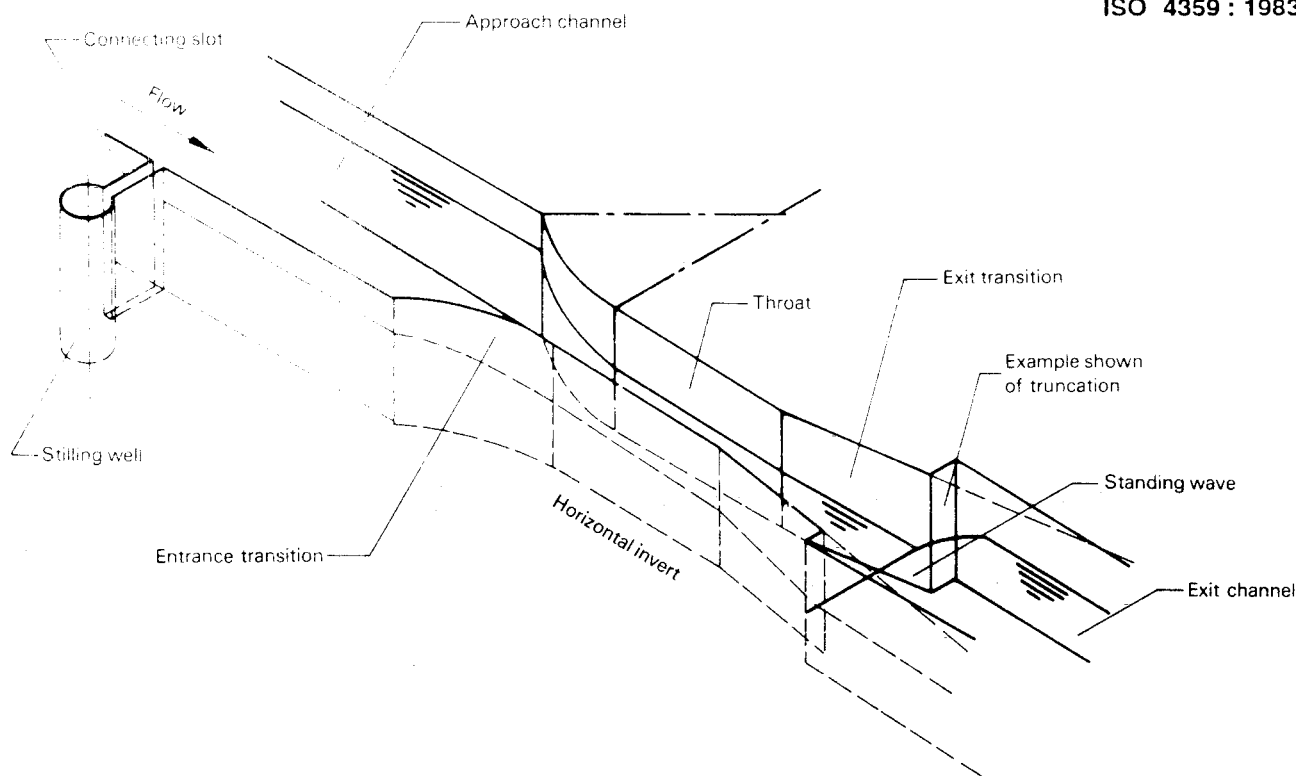
Table 4 — Recommended roughness values

Values in millimetres

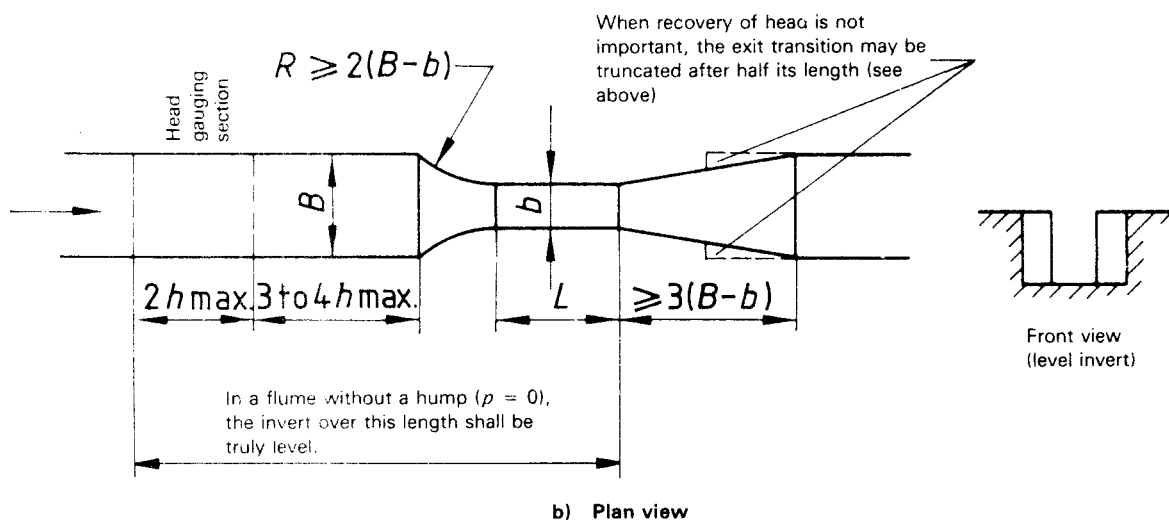
Surface classification	Values of k_s	
	Good example	Normal value
Plastics (and similar)		
Perspex, PVC or other smooth-faced plastics	—	0,003
Asbestos cement	—	0,015
Resin-bonded, glass fibre moulded against smooth forms of sheet metal or well-sanded and painted timber	0,03	0,06
Metal		
Smooth, machined and polished metal	0,003	0,006
Uncoated sheet metal, rust free	0,015	0,03
Painted sheet metal	0,03	0,06
Galvanized metal	0,06	0,15
Painted or coated casting	0,06	0,15
Uncoated casting	0,15	0,3
Concrete		
In-situ or precast construction using steel formwork, with all irregularities rubbed down or filled in	0,06	0,15
In-situ or precast construction using plywood or wrought timber formwork	0,3	0,6
Smooth trowelled cement rendering	0,3	0,6
Concrete with thin film or sewage slime	0,6	1,5
Wood		
Planed timber or plywood	0,3	0,6
Well sanded and painted	0,03	0,06

Table 5 — Viscosity of water

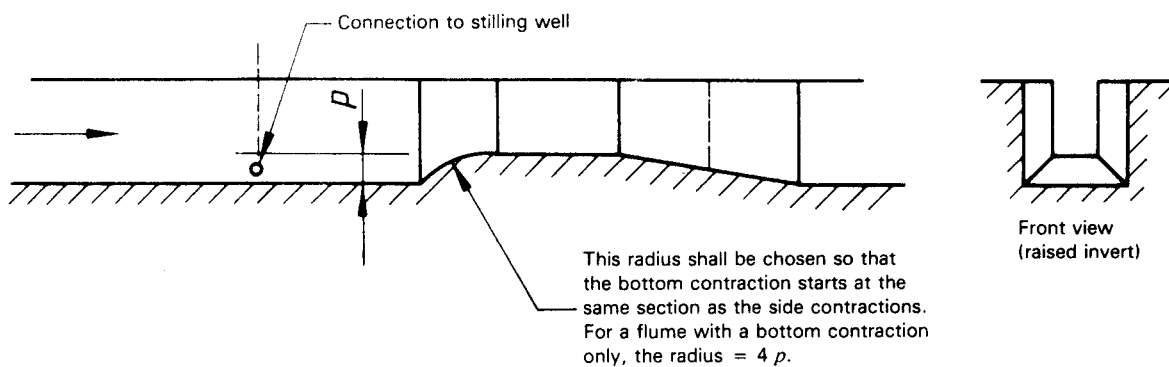
Temperature °C	Kinematic viscosity, ν m ² /s
0	$1,79 \times 10^{-6}$
5	$1,52 \times 10^{-6}$
10	$1,31 \times 10^{-6}$
15	$1,14 \times 10^{-6}$
20	$1,01 \times 10^{-6}$
25	$0,90 \times 10^{-6}$
30	$0,81 \times 10^{-6}$



a) Isometric view of level invert flume ($p = 0$)



b) Plan view



c) Longitudinal section of flume with raised invert (hump)

Figure 1 — Rectangular throated flume

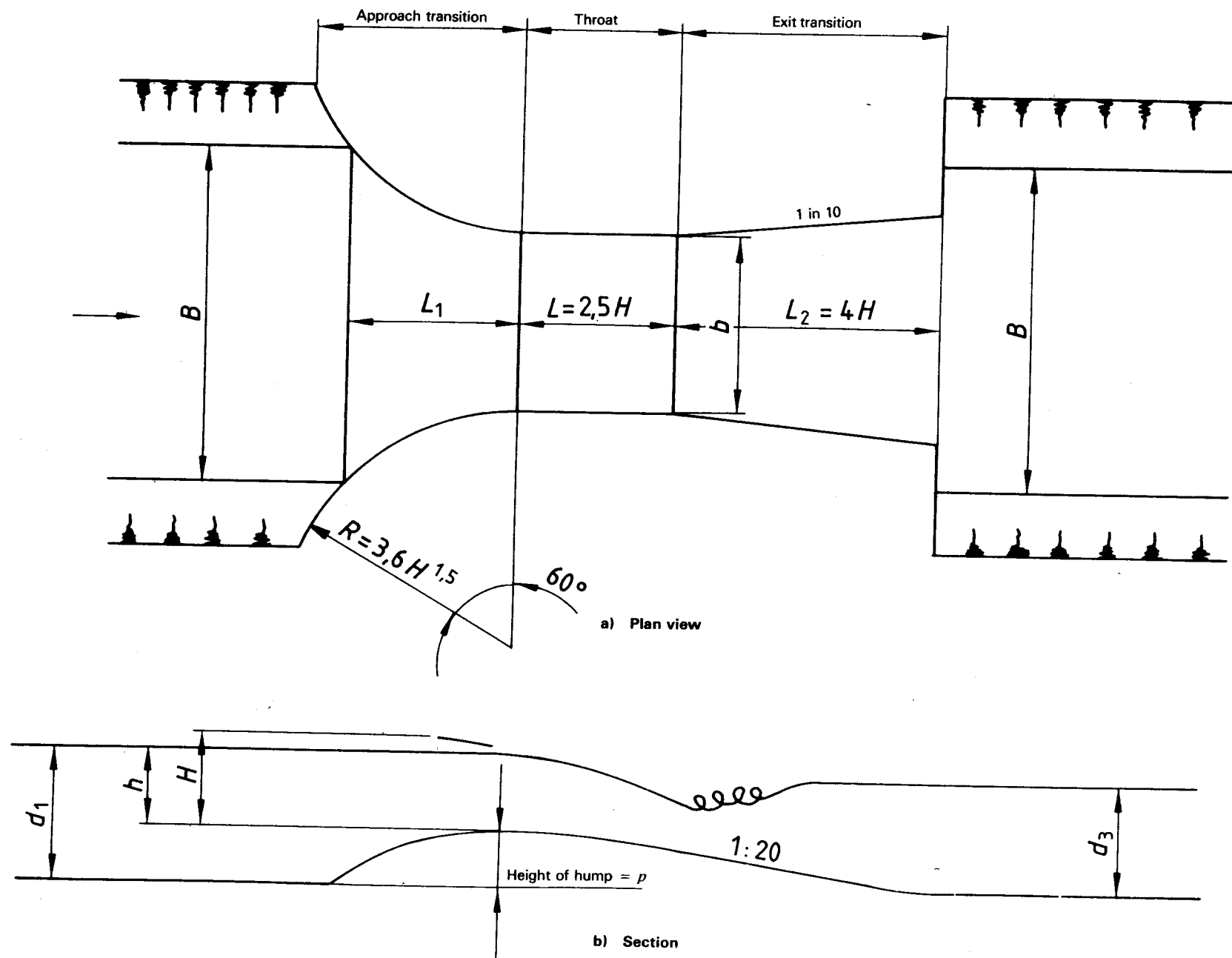


Figure 2 — Rectangular throated standing wave flume

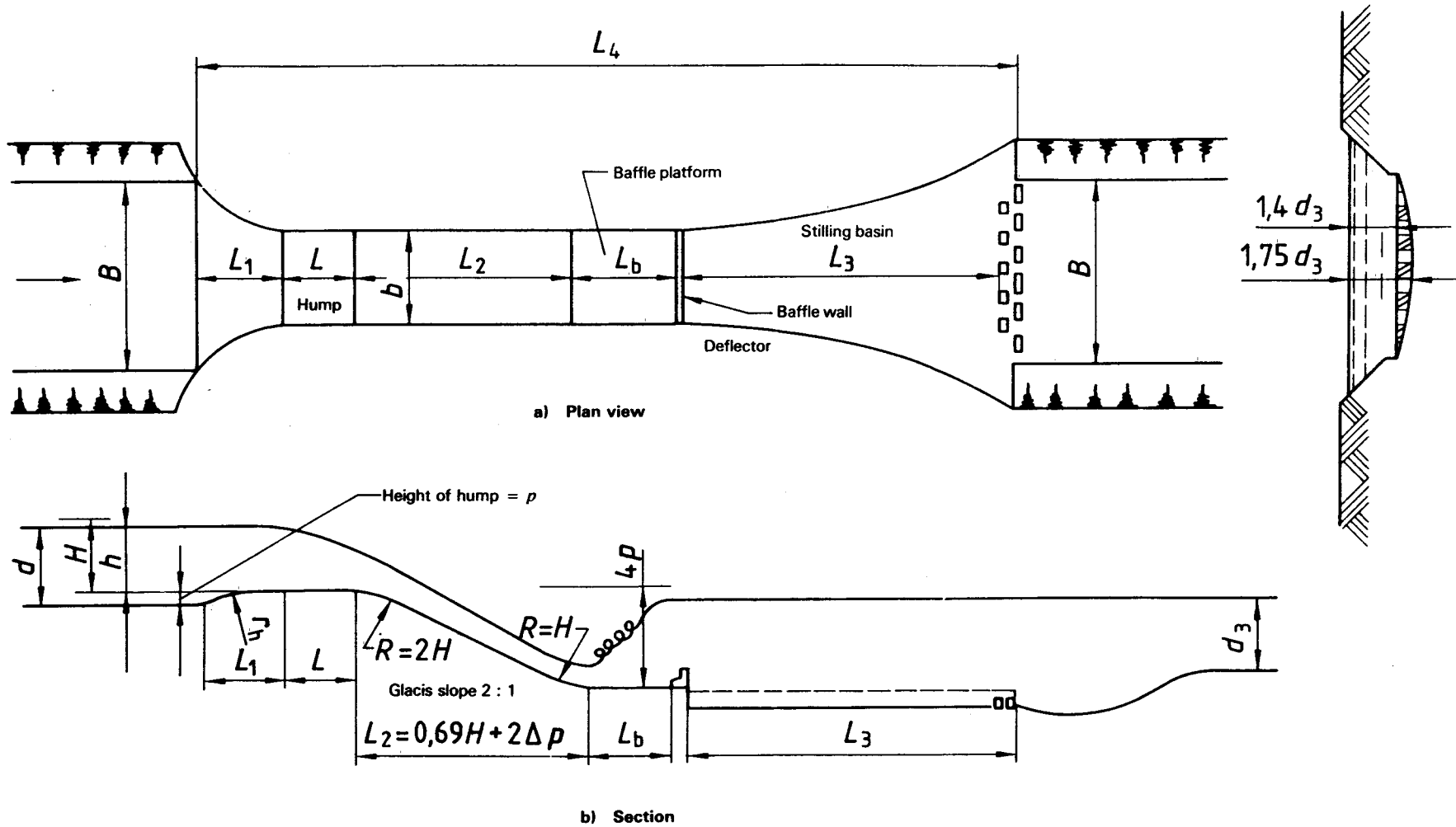


Figure 3 — Design of a flumed standing wave fall

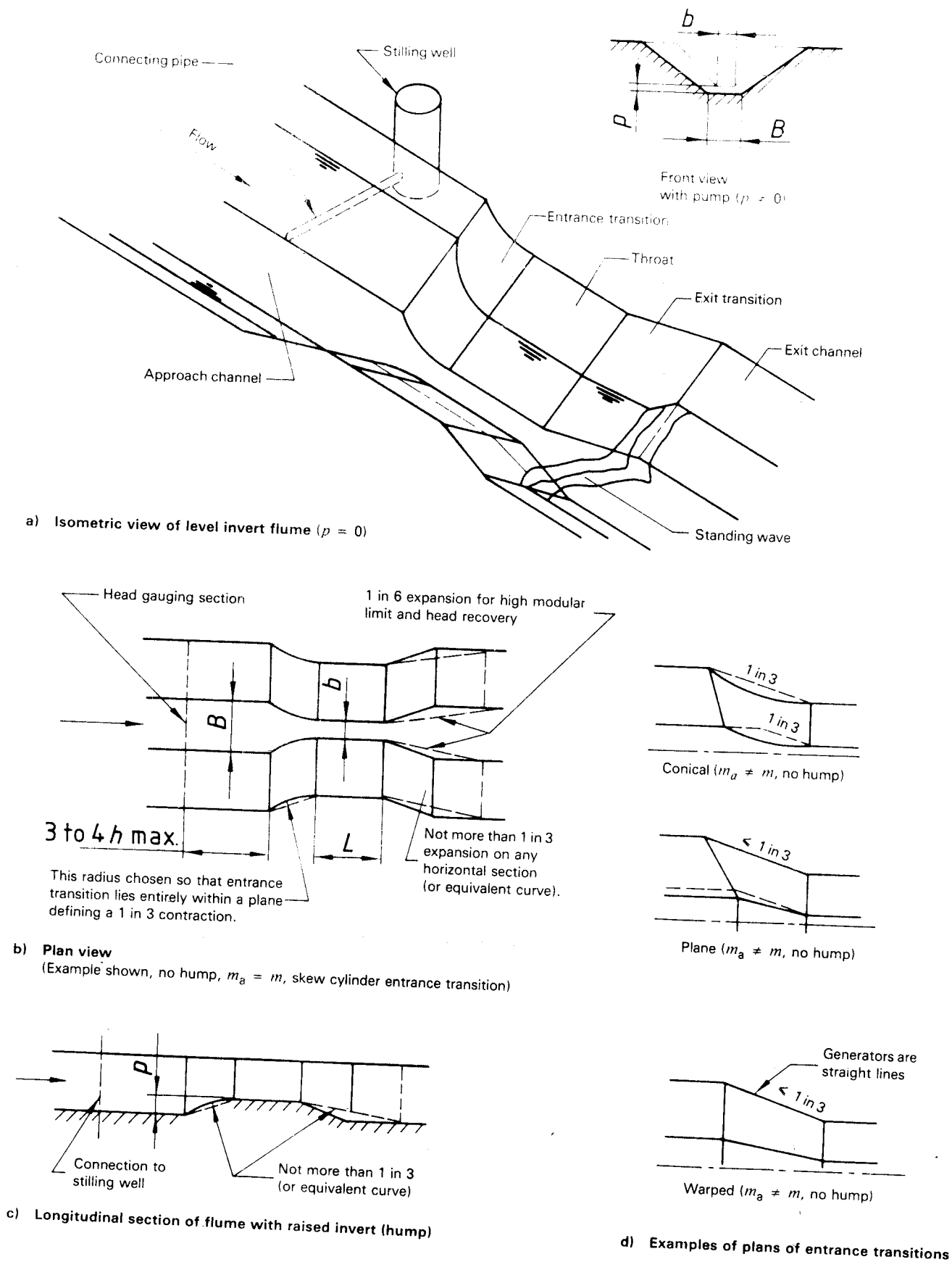
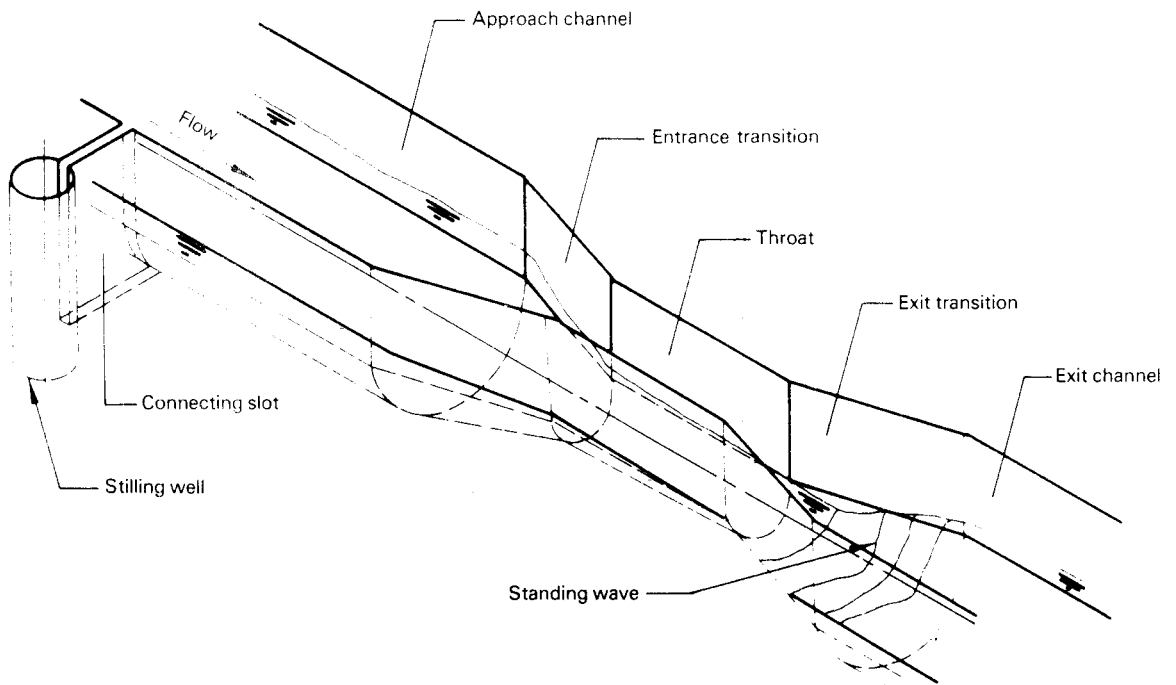
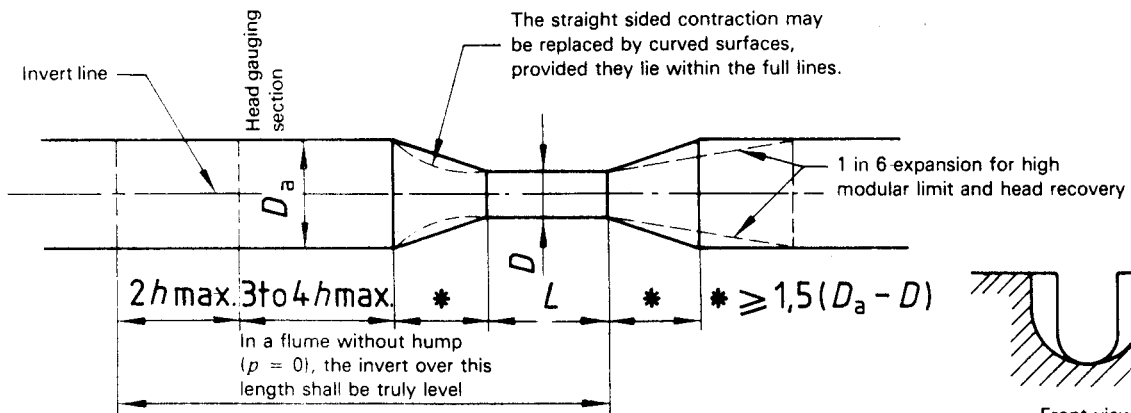


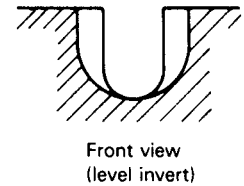
Figure 4 — Trapezoidal throated flume



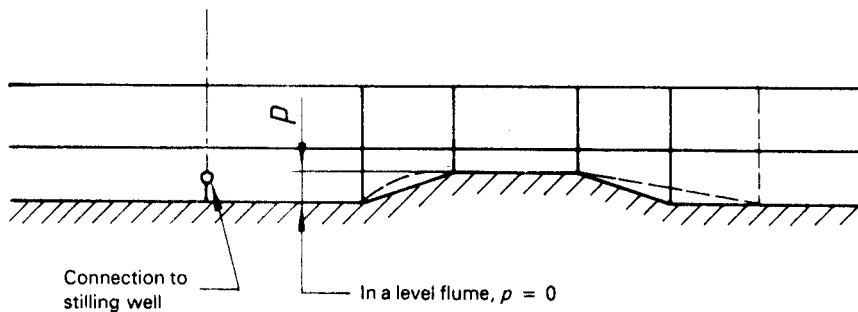
a) Isometric view



b) Plan view

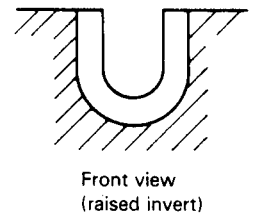


Front view
(level invert)



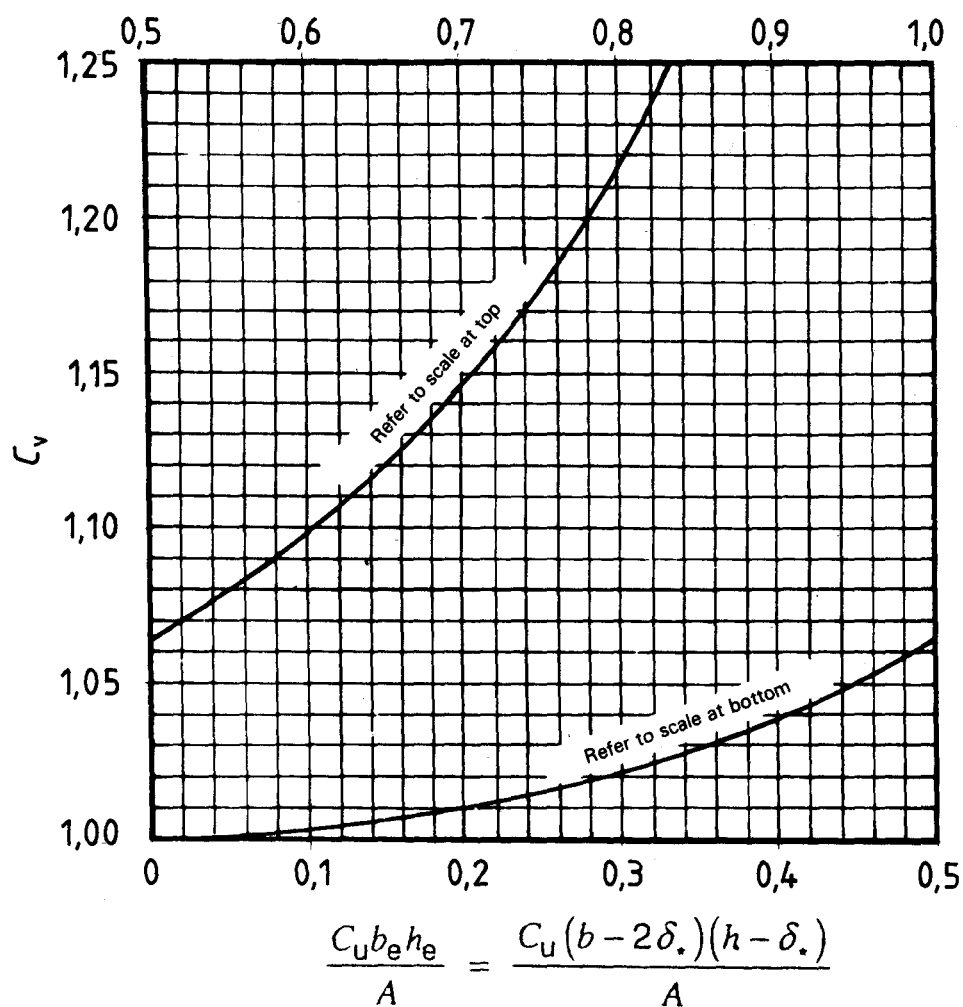
For a flume with a hump, a convenient value of p is $0,5 (D_a - D)$

c) Longitudinal section of flume with raised invert (hump)



Front view
(raised invert)

Figure 5 — U-shaped flume



NOTE — For a trapezoidal throat flume C_u is replaced by C_s . In a U-shaped flume $b = D$.

Figure 6 — Coefficient of approach velocity, C_v

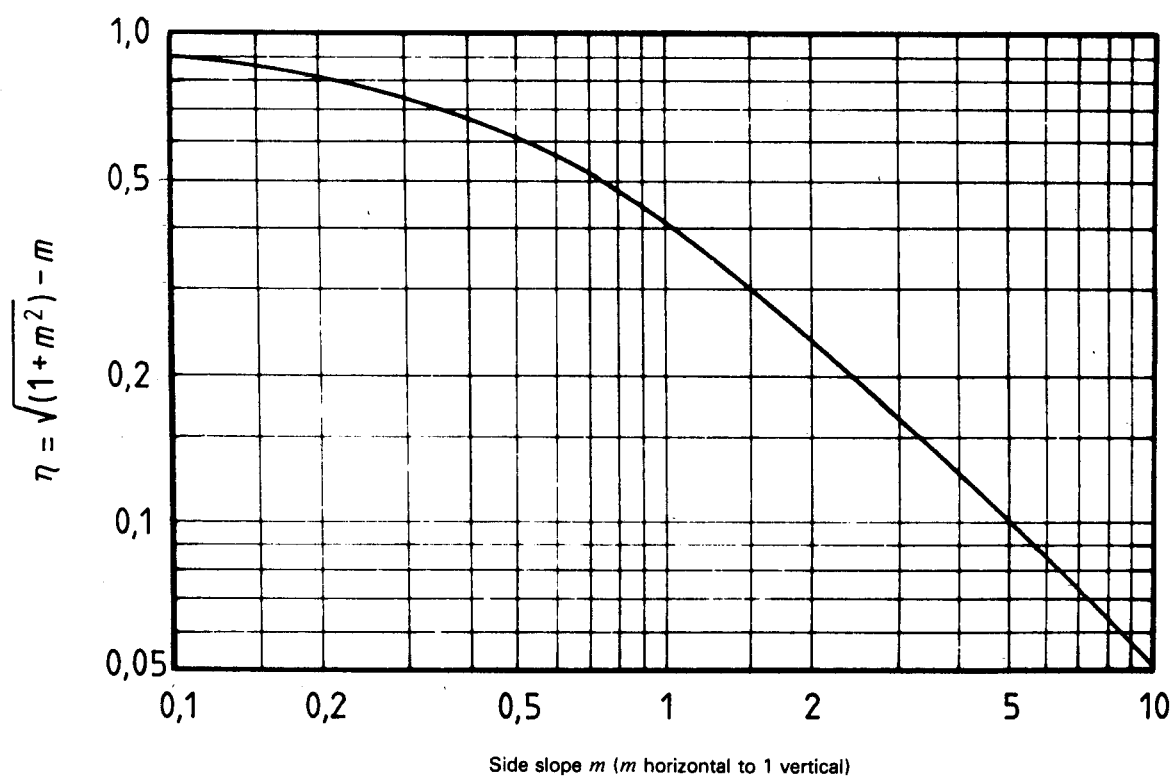
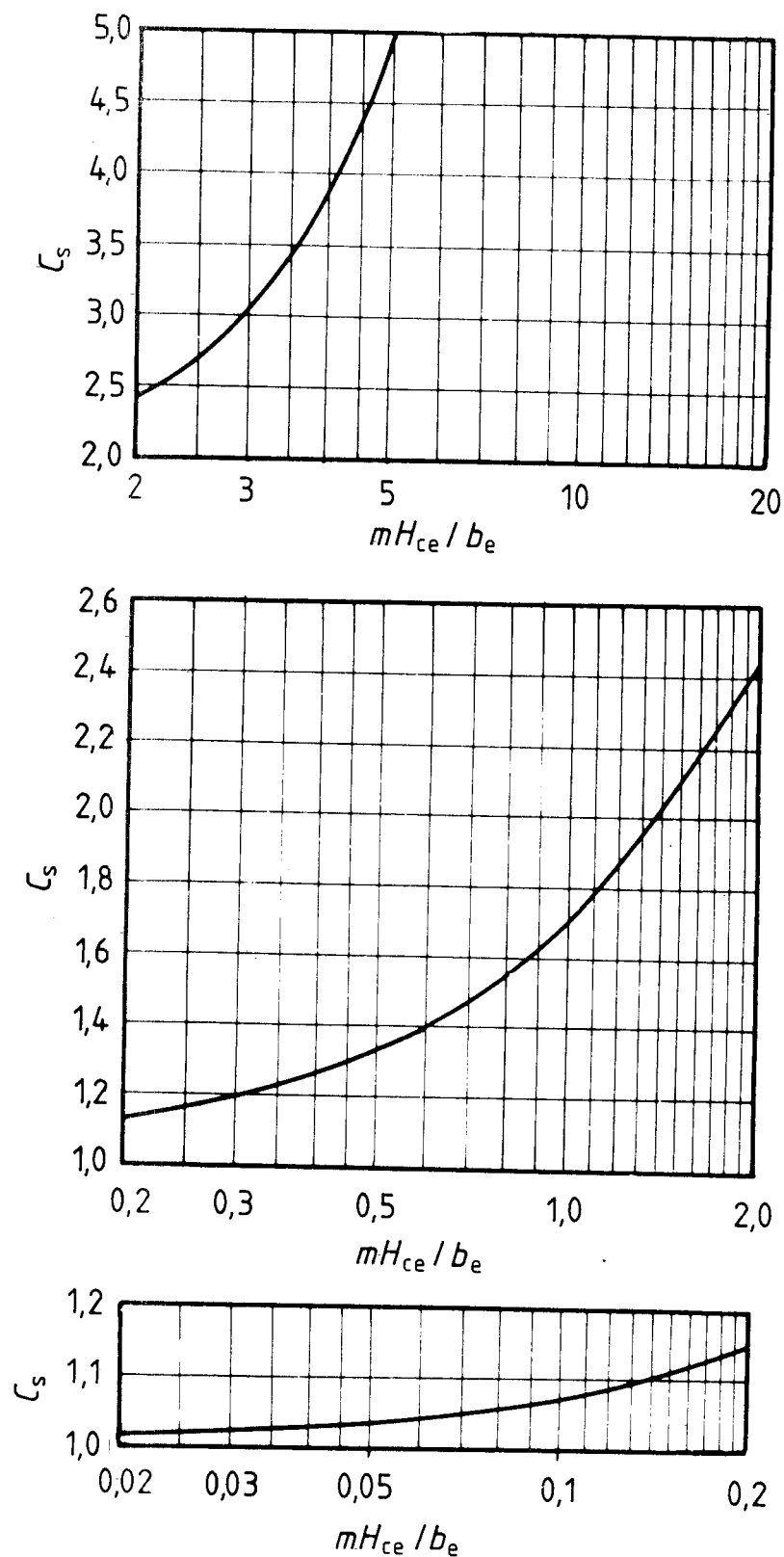
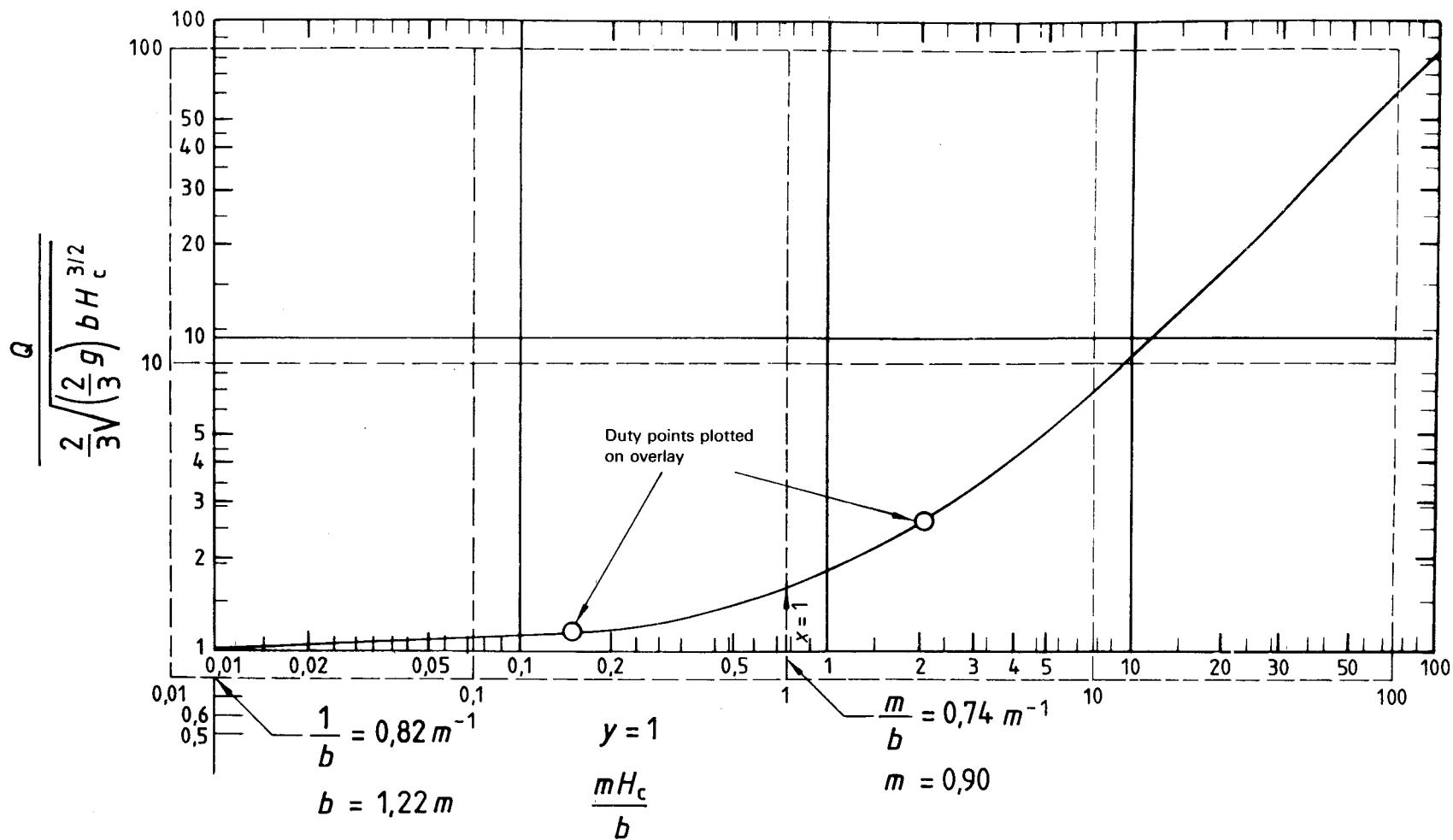


Figure 7 — Values of η for use in determining C_D : trapezoidal flumes



NOTE — If $mH_{ce} / b_e > 5$ obtain C_s from figure 9.

Figure 8 — Shape coefficient for trapezoidal flumes



NOTE — Broken lines indicate location of grid on overlay when in position.

Figure 9 — Design method using overlay for trapezoidal flumes

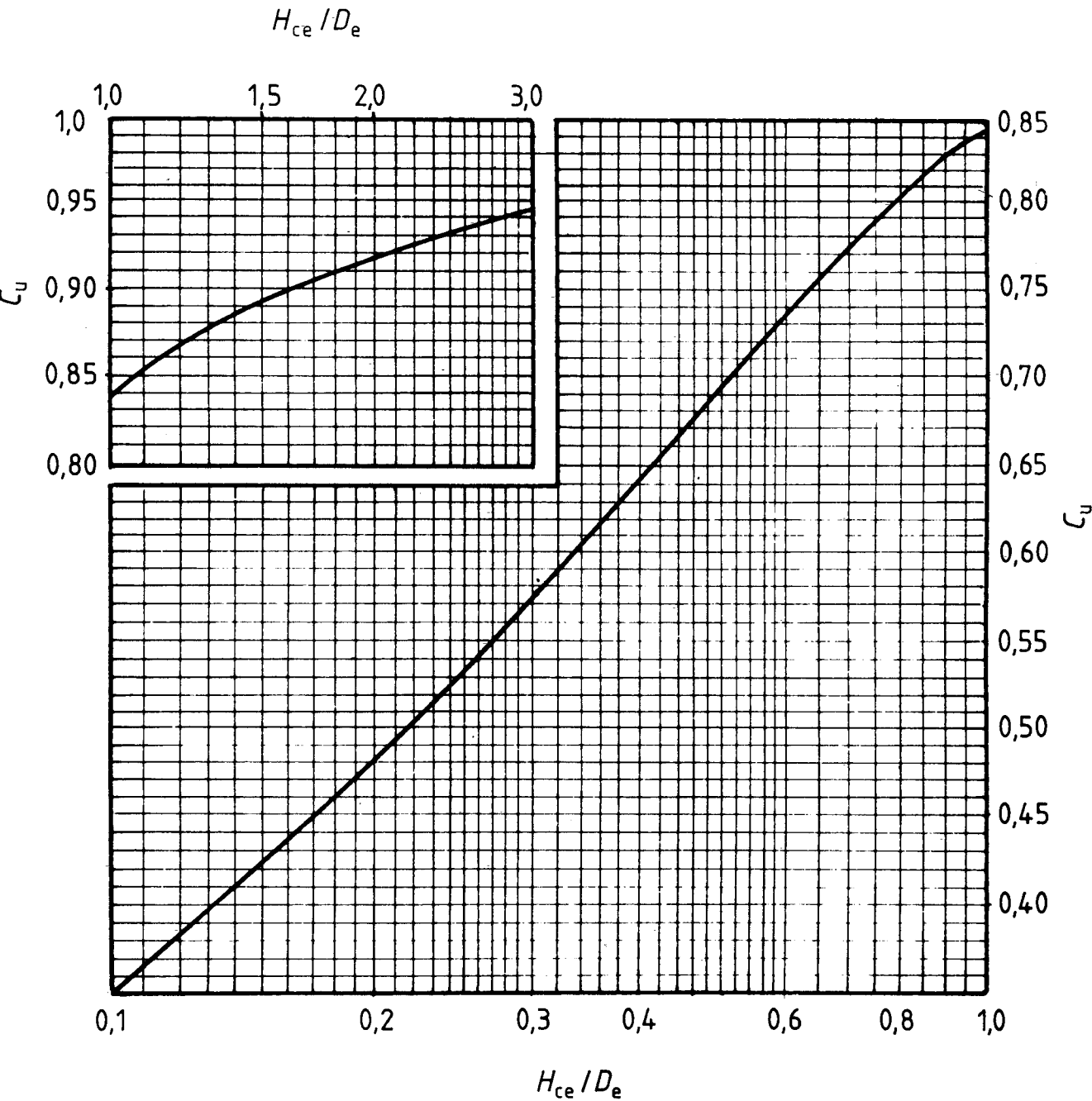
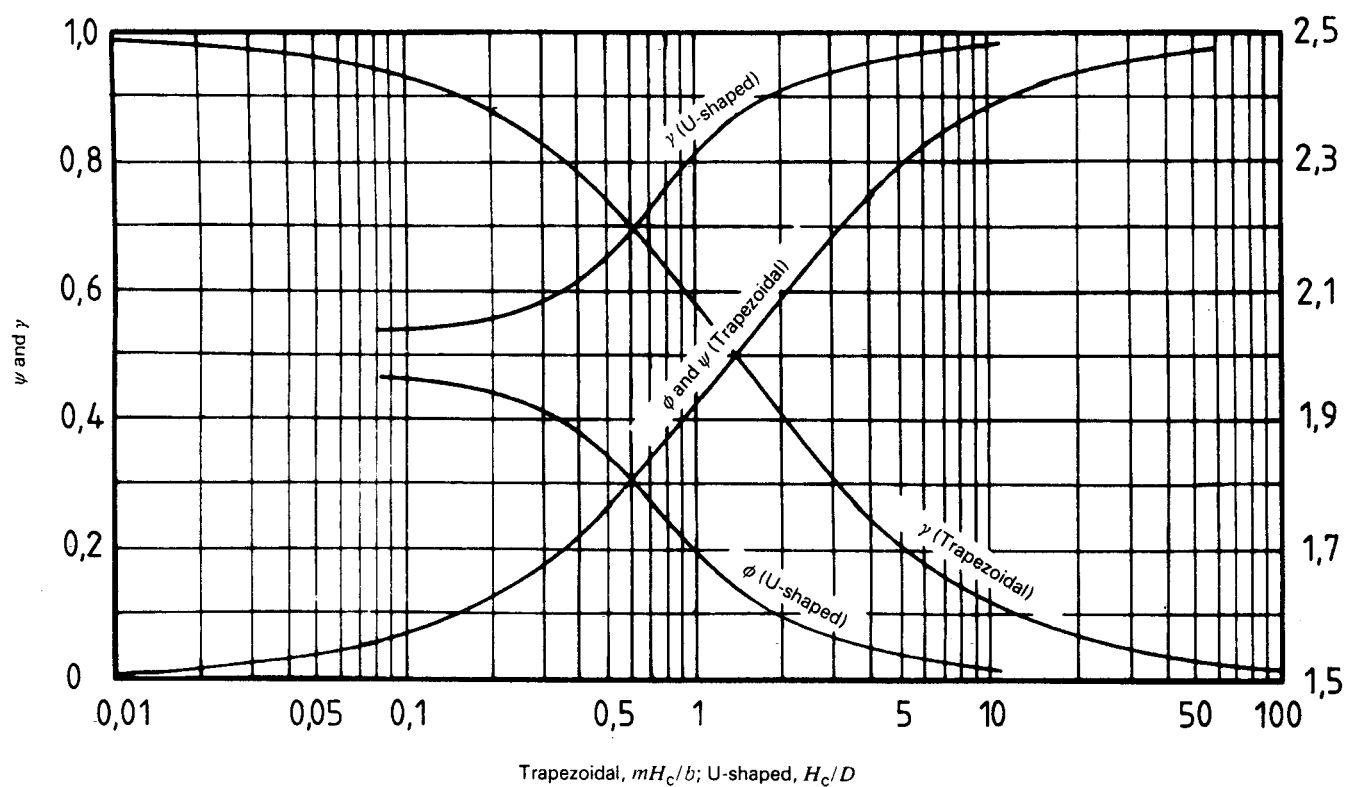
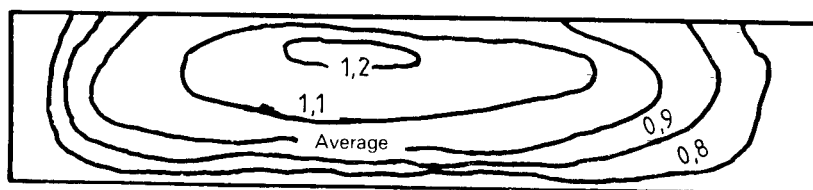


Figure 10 – Shape coefficient for U-shaped flumes



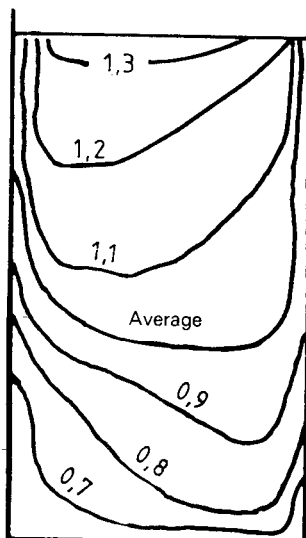
NOTE — $\psi = 0$ for U-shaped.

Figure 11 — Accuracy coefficients, γ , ψ , ϕ



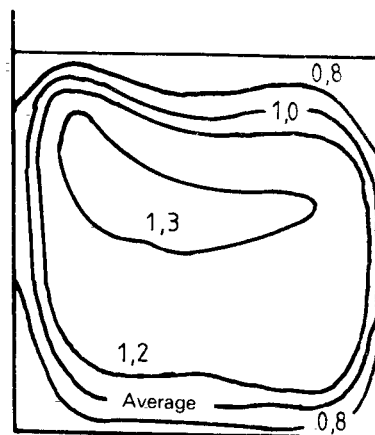
$$\left(\frac{\alpha_{\text{left}}}{\alpha_{\text{right}}} - 1 \right) \times 100 = 6,9 \%$$

a)



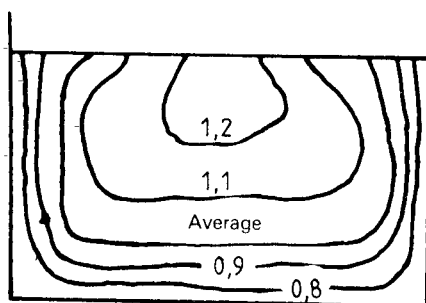
$$\left(\frac{\alpha_{\text{left}}}{\alpha_{\text{right}}} - 1 \right) \times 100 = 9,0 \%$$

b)



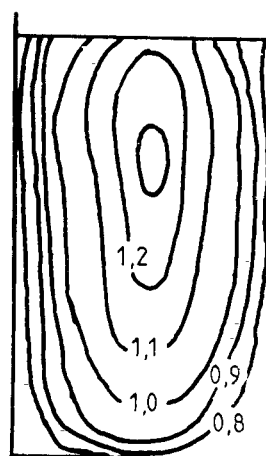
$$\left(\frac{\alpha_{\text{left}}}{\alpha_{\text{right}}} - 1 \right) \times 100 = 12,3 \%$$

c)



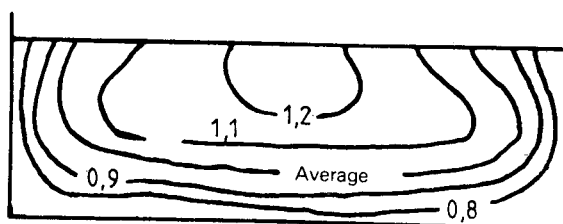
$$\left(\frac{\alpha_{\text{left}}}{\alpha_{\text{right}}} - 1 \right) \times 100 = 1,2 \%$$

d)



$$\left(\frac{\alpha_{\text{left}}}{\alpha_{\text{right}}} - 1 \right) \times 100 = 0,6 \%$$

e)



$$\left(\frac{\alpha_{\text{left}}}{\alpha_{\text{right}}} - 1 \right) \times 100 = 0,9 \%$$

f)

Figure 12 — Examples of velocity profile in approach channel

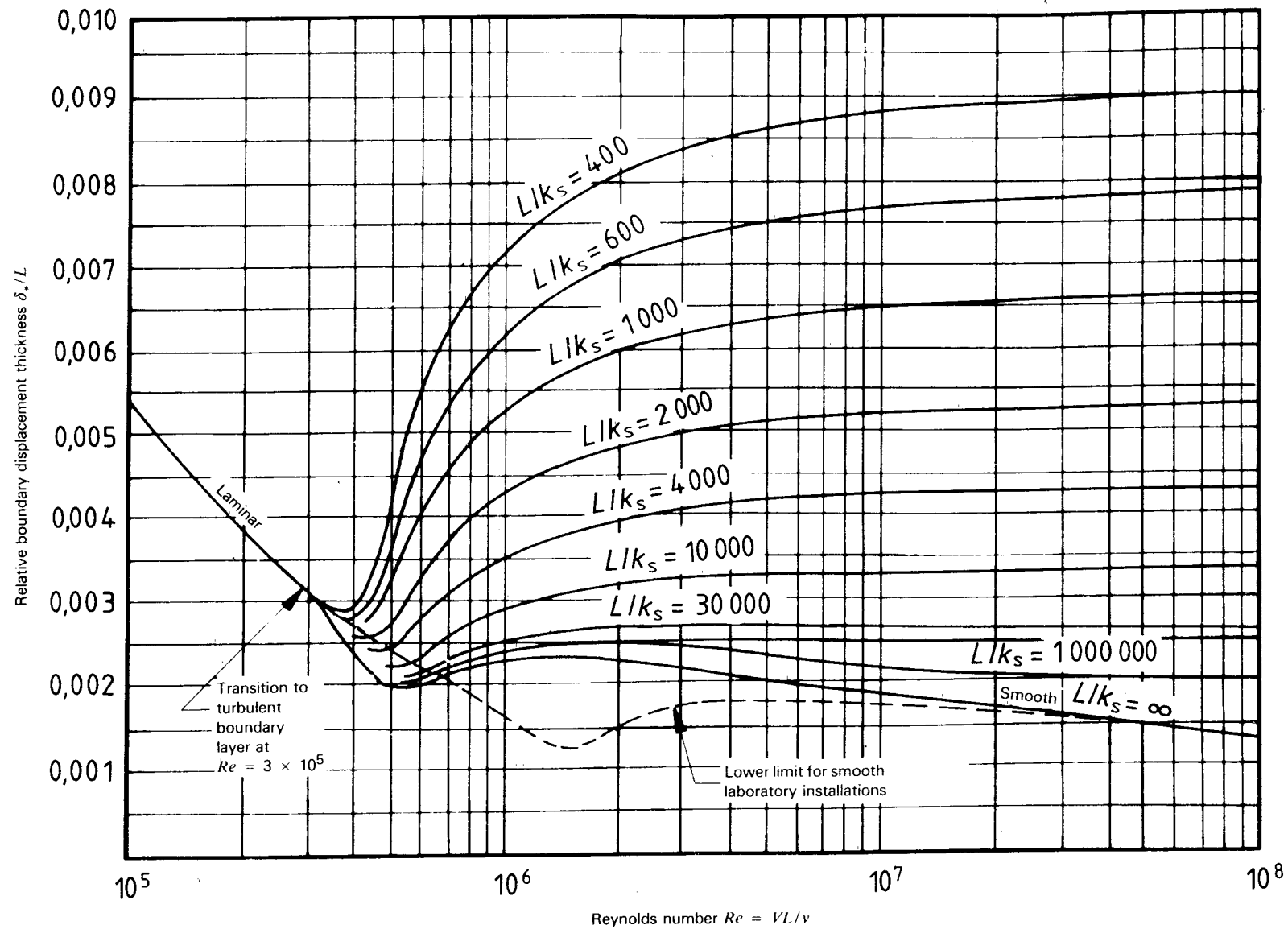


Figure 13 — Relative boundary layer displacement thickness

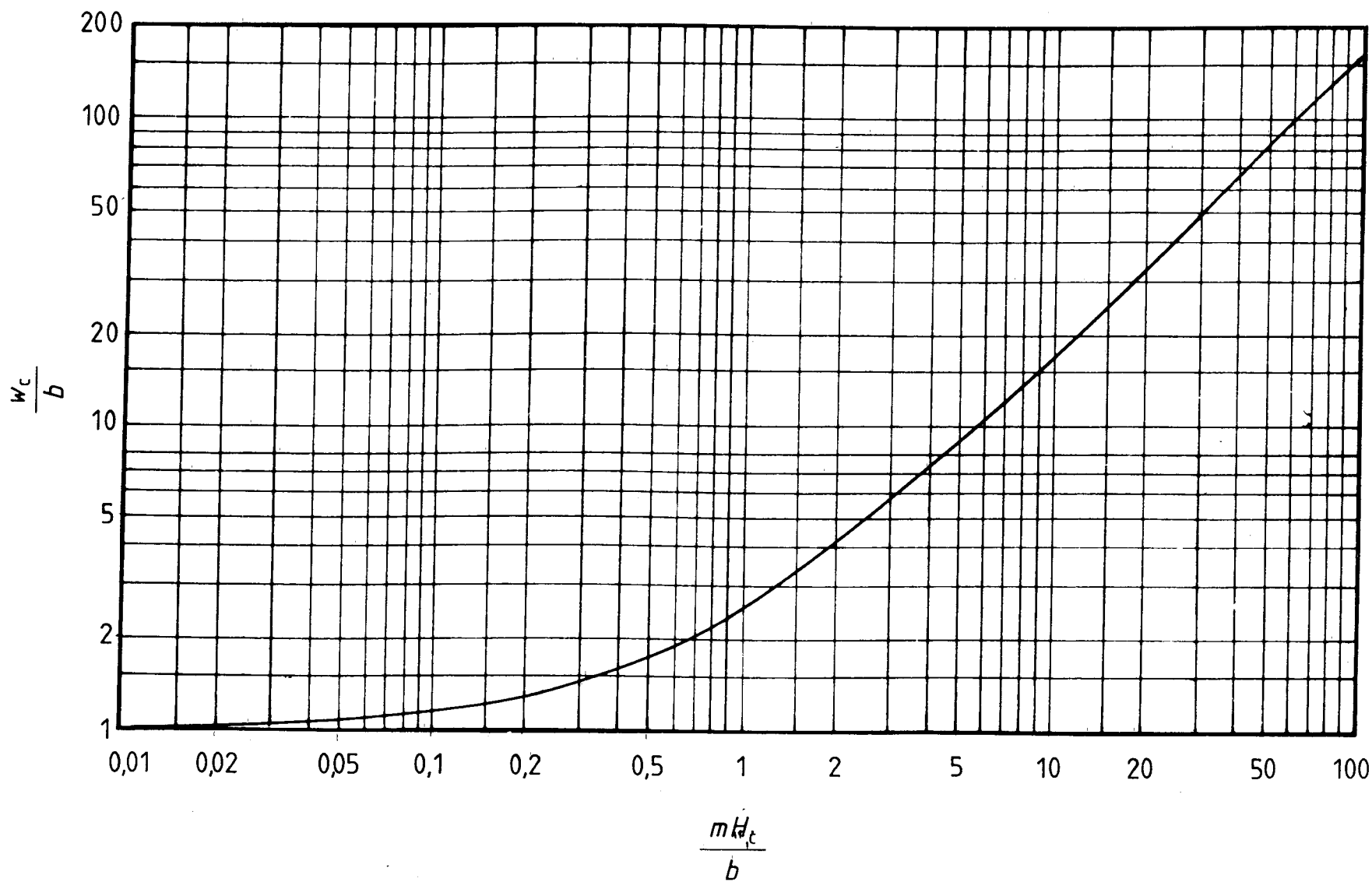
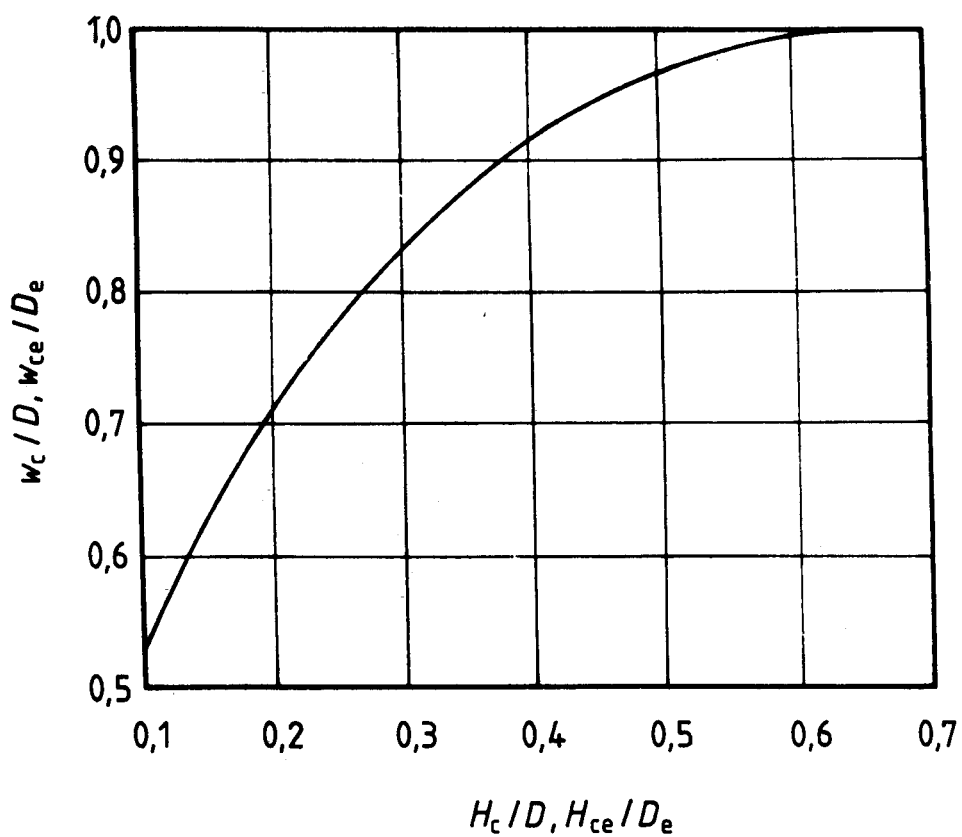


Figure 14 — Values of w_c/b for use in determining Re : trapezoidal flumes



NOTE — $w_c/D = 1.00$ when $H_c/D > 0.70$.

Figure 15 — Values of w_c/b for use in determining Re : U-shaped flumes

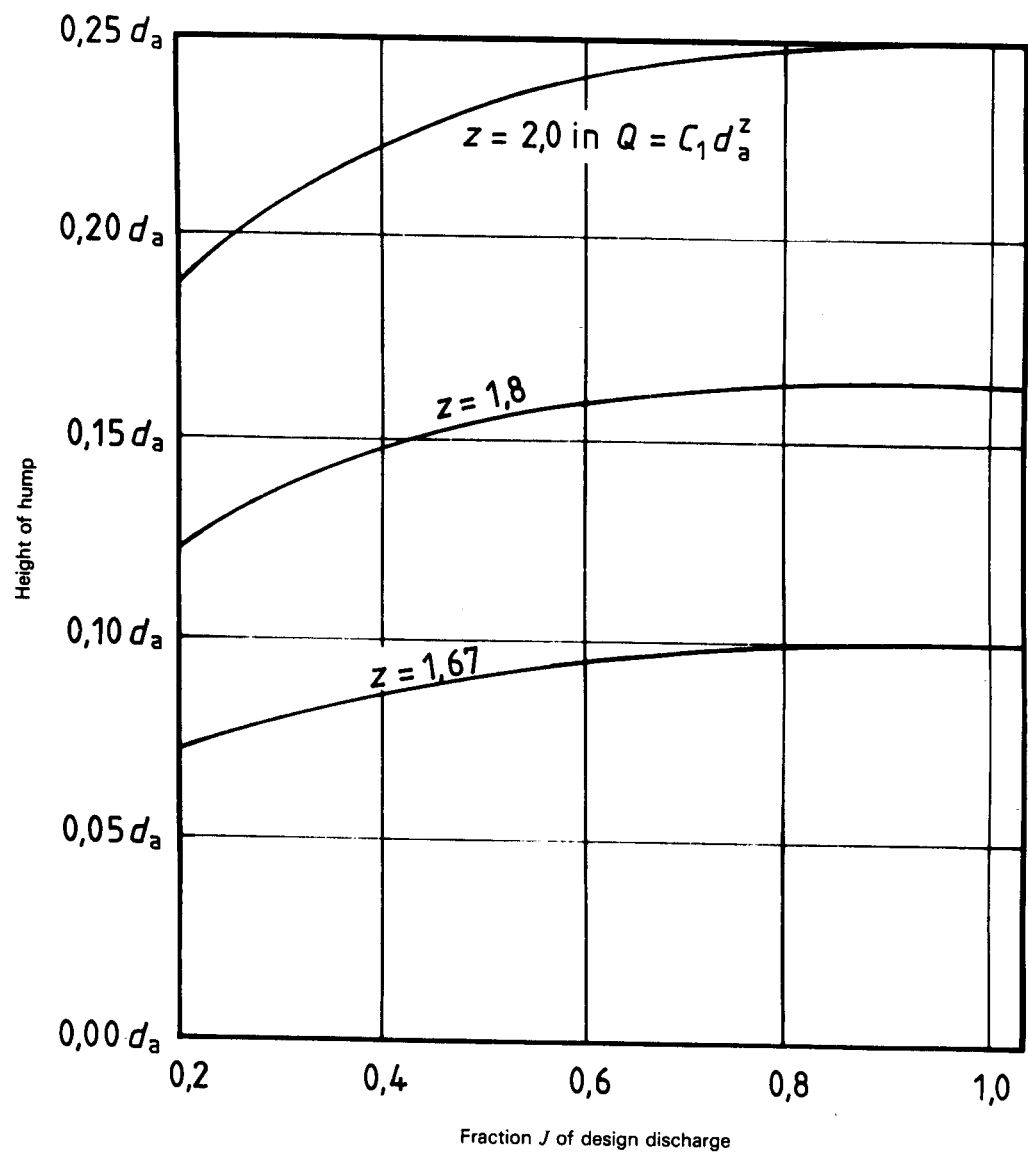


Figure 16 — Showing height of hump required to give proportionality for a small variation in discharge

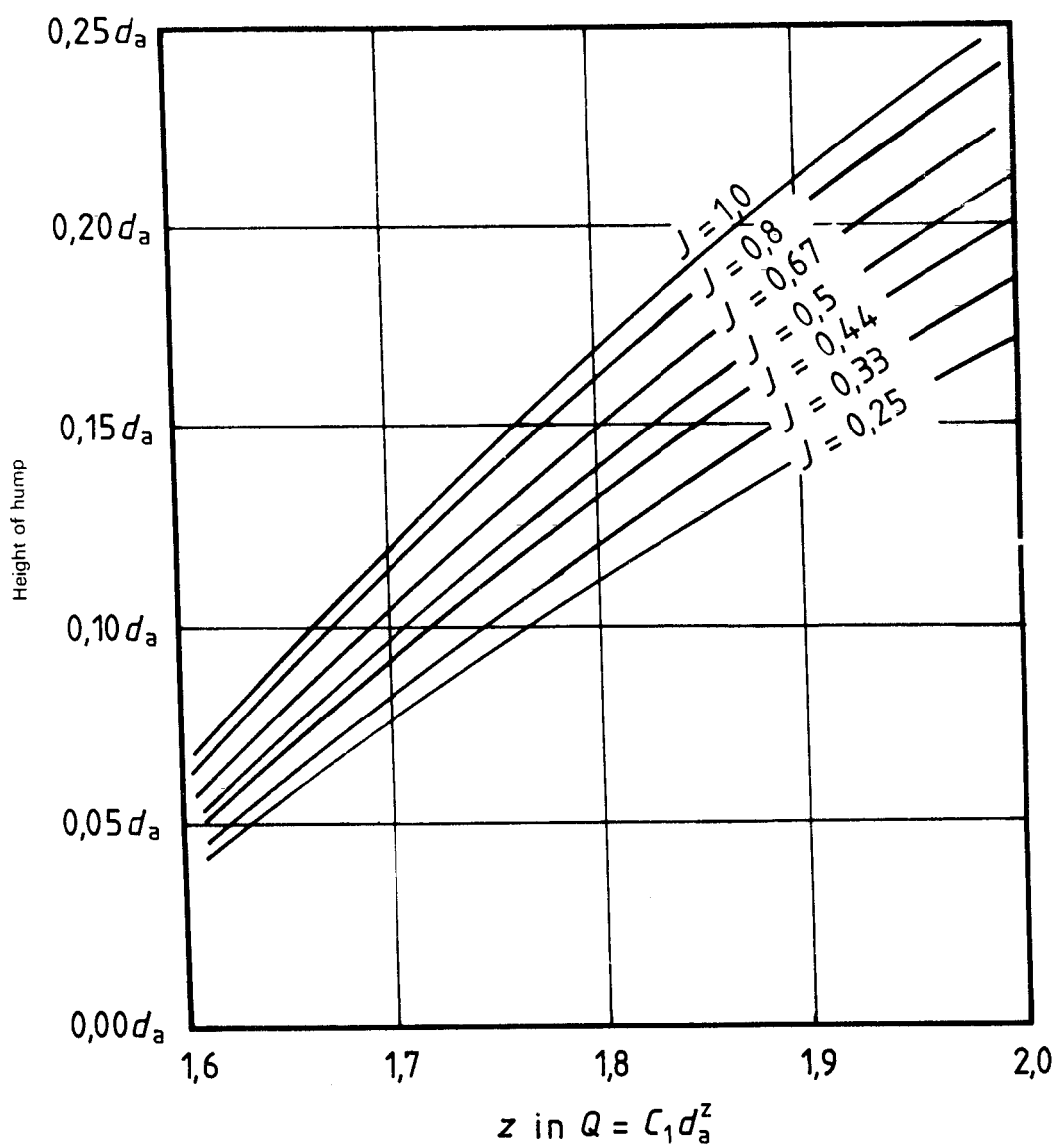


Figure 17 — Showing height of hump to attain bulk proportionality

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